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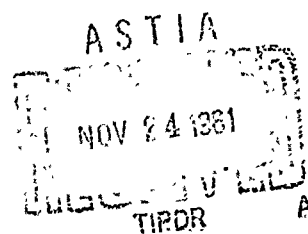# Behavior of Materials in Space Environments

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BEHAVIOR OF MATERIALS IN

SPACE ENVIRONMENTS

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CONTENTS

CONTENTS (Cont'd)

TABLES

TABLES (Cont'd)

FIGURES

FIGURES (Cont'd)

ABSTRACT

The quantitative effects of the environments encountered in various regions of space upon several kinds of engineering materials are discussed. In the vacuum of space, magnesium sublimes appreciably at elevated service temperatures; zinc and cadmium sublime at ordinary temperatures. Most other engineering metals will be unaffected by vacuum except for a slight surface roughening. Among the organics, polysulfides, cellulosics, acrylics, polyvinyl chloride, neoprene, and some nylons, polyesters, epoxys, polyurethanes, and alkyds break down at rather low temperatures in vacuum. Polyethylene, polypropylene, most fluorocarbons, and silicone resins do not decompose significantly in vacuum below 250°C. Except for plasticized materials, significant loss of engineering properties in vacuum is unlikely without appreciable accompanying sublimation or decomposition. Also, escape of gases through walls which are gas-tight at 1 atmosphere will not be of concern.

For parts intended to move in contact with each other in vacuum, lubrication is a serious problem. Certain low vapor pressure oils and greases, tetrafluoroethylene, and thin films of MoS_2, Au, and Ag can probably provide adequate lubrication when suitably selected for the speeds, loads, and times of service.

The particles of the Earth's radiation belts will cause radiation damage to organics and to optical properties of inorganic insulators. Semiconductors will be damaged in the inner belt; their more sensitive properties will also be affected by solar flare emissions. Exposed surfaces of most materials may be damaged by the radiation belts and perhaps by solar charged particle emissions. Optical properties of exposed polymers and ceramics will also be affected by solar ultraviolet and X-rays. Sputtering away of material by collision with ions or atoms in space is probably negligible.

Erosion by meteoroids is significant only close to the Earth. The probability of penetration by meteoroids falls sharply with increasing distance from Earth. Much more frequent than penetration is spalling of fragments from the inside of walls struck by meteoroids. The efficiency of walls in preventing penetration and spalling can be increased by splitting the walls into a thin front plate and a thicker main plate; quantitative bases for the design of such spaced armor are presented.

I. INTRODUCTION

Special problems relating to the behavior of materials in outer space arise both from the absence and the presence of surrounding matter--that is, from vacuum and from particles in space. Although in the last few years much infor-mation has been gained with respect to the nature of these particles and the effect that they have upon materials, the gaps in our knowledge remain great. However, in order to design and build equipment to operate in space, we must form engin-eering judgments on the basis of available information. This paper attempts to synthesize the best of the current information while discarding that which is no longer applicable.

II. MATERIALS AND ENVIRONMENTS CONSIDERED

The materials considered here are those likely to be used in space vehicles, spacecraft, and space experiments: metals, ceramics, semiconductors, plastics, elastomers, paints, greases, and oils. Living materials are not included; considerable attention has been devoted to them elsewhere.

The region of space considered extends from the minimum altitude for an Earth satellite--say 200 km (125 miles) from the Earth's surface--to the orbits of Venus and Mars and close to the plane of the ecliptic (the Earth's orbital plane). Conditions within a million km of Venus and Mars are not con-sidered.

It should be recognized that the region discussed is not homogeneous. The composition of the gas at 200 km from the Earth differs widely from that at a million km; the micrometeoroid concentration may differ by a factor of 10^4; the electron flux differs by even larger factors over small distances. Thus, even within the limited region of space considered, there is not a single "space environment" but a range of environments.

Environments introduced by a spacecraft itself, such as vibration associated with the launch, high temperatures arising from propulsion combustion, low temperatures arising from cryogenic propellants, and radiation from onboard nuclear reactors, are not considered in this paper since they are not peculiar to space.

III. VACUUM EFFECTS

A. The Vacuum of Space

The range of gas pressures encountered in space is indicated in Table 1. The pressure falls from about 10^3 mm Hg at the Earth's surface to 10^{-6} mm Hg at 200 km (125 miles) and less than 10^{-12} mm Hg beyond 6500 km (4000 miles) altitude. As 10^{-6} mm is a typical pressure for a good laboratory high-vacuum system, and 10^{-12} mm is about the best vacuum that has ever been achieved in the laboratory, these figures show that space is a very good vacuum indeed.

Although approximate temperatures of the gas in space are indicated in the table, these temperatures have no significant effect upon the temperature of

a spacecraft. The spacecraft temperature is determined by the balance between heat received by radiation from Sun, Earth, and Moon, heat radiated out by the spacecraft, and heat generated by equipment aboard the spacecraft. The temperature control problem is important in choosing materials for use in space, since the heat absorbed and the heat radiated vary directly with the absorptivity and emissivity of the outer surfaces at appropriate optical wavelengths. Considerable attention has been devoted to this problem (19); it will not be dealt with here, except for changes in optical absorptivity and emissivity which may be caused by the space environment.

B. Loss of Inorganic Materials in Vacuum

The problem which first comes to mind in considering the behavior of materials in space is that of evaporation or sublimation into the space vacuum. The rate at which molecules leave a surface into vacuum is given by the Langmuir equation (20-22), which dates from 1913:

$$W = \frac{p}{17.14} \sqrt{\frac{M}{T}} \tag{1}$$

where

W = rate of evaporation or sublimation, in gm/cm^2-sec

p = vapor pressure of the material, mm Hg

M = molecular weight of the material in the gas phase

T = temperature, °K

This may be put in the form (23):

$$S = 1.85 \times 10^6 \, \frac{p}{\rho} \sqrt{\frac{M}{T}} \qquad (2)$$

where

S = rate of sublimation, cm/yr

ρ = density of the solid material, gm/cm^3

These equations give the rate of evaporation or sublimation when none of the molecules leaving the surface return to it. If the vacuum is poor, so that evaporating molecules can collide with air molecules and be scattered back to the surface, the net rate of loss will be lower, but it can never be higher. (Note that the sublimation rates W and S increase with temperature, even though $\sqrt{T}$ is in the denominator, because the vapor pressure p increases rapidly with temperature.)

For most elements and inorganic compounds likely to be of interest, the vapor pressures and molecular weights are well known. Accordingly, it is not necessary to carry out any experiments to determine rates of sublimation of such materials in vacuum; they can be calculated with confidence from Eq. 1 or 2. Results for elemental metals and semiconductors are given in Table 2 in terms of the temperature at which various amounts of thickness per year will be lost from a surface. For comparison, melting points are also given in the table.

Table 2 shows that appreciable loss of cadmium and zinc, which are commonly used as platings, will occur at temperatures likely to be encountered by these materials in spacecraft. Selenium, sometimes used in photocells, will

likewise sublime. Magnesium, on the other hand, will not lose as much as 10^{-3} cm/yr (0.0004 in./yr) unless its temperature reaches about 170°C (340°F). This amount is too small to be of structural significance; it might be important if the magnesium were used as a thin film for, say, optical purposes. At about 240°C (470°F), 10^{-1} cm (0.040 in.) of magnesium will sublime per year; such a loss will usually be very significant structurally. Most other metals such as aluminum, as well as the semiconductors germanium and silicon, will not lose significant thickness except at much higher temperatures. Many of these materials may, it is true, be expected to operate at high temperatures in spacecraft.

A metal as ordinarily used is not homogeneous but is composed of millions of microscopic crystals or "grains." When the metal is exposed to vacuum at a temperature where sublimation occurs, the loss will not be even over the surface but, because of differences in crystal orientation, slightly faster on some grains than others. This selective loss is also directional, so that the exposed surfaces of individual grains do not remain parallel to the original position of the surface or to each other. Because metals, except for thin films or foils, are usually many grains thick, selective losses of this type will average out as they progress through the metal and will not lead to deep holes. The chief result of engineering interest will be a roughening of the surface on a microscopic scale.

A related effect is the accelerated sublimation which takes place at the boundaries between grains. Fears have been expressed that this will lead to development of holes extending completely through a metal wall. This grain boundary sublimation cannot, however, progress to a depth exceeding a fraction

of the grain diameter because of a balancing of surface tension forces which arises as the boundary etches away (25-27). In ordinary polycrystalline material, the grain boundary attack will thus be shallow, and the only practical result is likely to be, again, a microscopic roughening.

When alloys are used in the vacuum of space, some thought may be given to the possibility of loss of the more volatile constituents. Unless the temperature is high enough to permit diffusion of the volatile elements through the solid alloy, loss can occur only from a surface layer 1 ↔ 2 atoms thick. Brass, which contains 30 to 40% of volatile zinc, is commonly used in laboratory vacuum systems at temperatures up to several hundred degrees with no difficulty from loss of zinc. To permit diffusion of atoms from inside the alloy to its surface, and so continue loss of the volatile element, the temperature must generally be high enough so that the material is in an "elevated temperature" regime in the sense that the material will creep significantly under load. This "elevated temperature" may be 120° C (250° F) for aluminum base alloys, 550° C (1000° F) for steels, and several thousand degrees for tungsten-base alloys. Even at these temperatures, the maximum loss rate from the alloy will be less than that from the pure volatile metal in proportion to the composition of the alloy. For example, the commercial aluminum-base alloy 7075 contains 5.5 weight percent zinc, equivalent to 2.3 atomic percent. At 150° C (300° F), Table 2 indicates an appreciable loss rate for pure zinc, and the temperature may be high enough that diffusion from inside to surface may occur. Since only 2.3 atomic percent zinc is present, the loss rate (gm/cm^2-yr) will not exceed about 2% of the rate for pure zinc. In fact, measurements (28) show that the loss of zinc and cadmium

from silver-zinc and silver-cadmium alloys is many orders of magnitude less than for pure zinc and pure cadmium, even at 650° C (1200° F).

For inorganic compounds, the problem is a bit more complex, because loss may occur by several mechanisms. First, molecules of the compound may sublime. For calculation of the weight loss by this mechanism, vapor pressure data can usually be found in the literature. If vapor pressures are measured, but not at temperatures of interest, approximate values can be obtained by extrapolation, using the relation

$$\log p = C - \frac{B}{T} \tag{3}$$

where C and B are constants. This relation is derived from the Clausius-Clapyron equation of thermodynamics (29). Once the vapor pressure is known for the appropriate temperature, the loss rate can be calculated by Eq. 2. Loss rates obtained in this way, for a few compounds, are given in Table 3.

Another process which may take place in inorganic compounds is decomposition to the elements or to simpler compounds, some of which may be volatile. For example,

$$MoS_2(s) \longrightarrow Mo(s) + S_2(g) \tag{4} \qquad K = p_{S_2} \tag{4A}$$

$$MgO(s) \longrightarrow Mg(g) + \tfrac{1}{2} O_2(g) \tag{5} \qquad K = (p_{Mg})(p_{O_2})^{\frac{1}{2}} \tag{5A}$$

$$2CeO_2(s) \longrightarrow Ce_2O_3(l) + \tfrac{1}{2} O_2(g) \tag{6} \qquad K = (p_{O_2})^{\frac{1}{2}} \tag{6A}$$
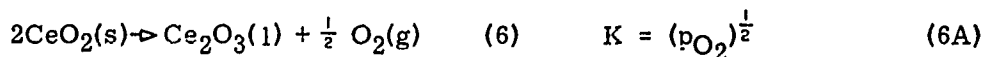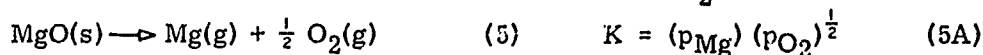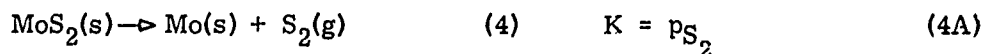
The rates of loss by such a reaction can be calculated from the equilibrium constant K, which is the product of the pressures (in atmospheres) of the gaseous

products, each raised to a power equal to the coefficient of the corresponding term in the chemical equation (Eq. 4A-6A). If K is known, the decomposition pressure is readily computed by this relation and can be substituted in Eq. 1 or 2 to give the loss rate, K values are usually obtained from tabulated values of the free energies for the compound and its decomposition products by the equation

$$\Delta F = -RT \ln K \tag{7}$$

where ΔF is the change in free energy in the reaction and R is the universal gas constant.

As an example, Eq. (4) gives for MoS_2 a weight loss by decomposition 10^6 times as great as that due to sublimation.

Inorganic compounds, especially ceramics, may also suffer loss of a volatile element in such reactions as

$$ThO_2(s) \rightarrow ThO_{1.95}(s) + aO_2(g) \tag{8}$$

$$UC(s) \rightarrow U_{0.8}C(s) + bU(g) \tag{9}$$
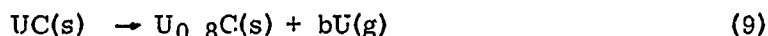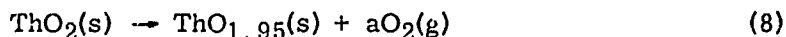
Here, $ThO_{1.95}$ and $U_{0.8}C$ are the same phases as ThO_2 and UC, respectively; a change of composition has occurred within the limits of phase stability.

A complex inorganic material of considerable engineering interest is glass. Borosilicate glass is the standard material of construction for laboratory ultra-high vacuum systems which withstand baking at 450°C (840°F). Accordingly, sublimation and decomposition of borosilicate glass should not be a problem, at least up to this temperature.

A special problem may arise, particularly with electronic equipment, if a material which is somewhat volatile or unstable is used in a partial enclosure that is exposed to space vacuum and in which considerable temperature differences exist. Metal may then sublime from warm areas and condense on cold insulating surfaces in the form of a thin film, which could cause a short circuit. Cadmium, zinc, and magnesium are most likely to cause this trouble. Similarly, a compound may sublime or decompose and the products may redeposit as an insulating layer on a cooler surface intended to conduct electricity or heat, such as a relay contact. This could interfere with proper operation. The thickness deposited may be estimated by first calculating the amount sublimed or decomposed, using Eq. 2 or Table 2 or 3. Multiplying this by the ratio of over-all warm area to over-all cold area gives an upper limit to the thickness condensed (because some material will be lost into space). A metallic deposit will not be continuous and so will not be conducting unless the deposit is thicker than the diameter of an atom, about 5 $\overset{\circ}{\mathrm{A}}$. If the possible metal thickness is greater than this, the thickness estimate can be used to compute the minimum possible resistance of the film. For insulating deposits, the thickness estimate can be used similarly to compute the maximum possible breakdown voltage or film resistance.

Concern has occasionally been expressed that metals, in particular, will grow or deposit as long thin crystals ("whiskers") which may short-circuit electrical insulators or gaps. Since whisker growth of this sort generally occurs from a supersaturated vapor phase or in connection with oxidation, it seems much less likely in space than on Earth.

One way in which it should be possible to reduce sublimation is by surface coating. Platings or paints of various sorts can be used. On metals, "chemical conversion" coatings are widely used for other purposes. These "conversion" coatings are mostly oxides and phosphates, which are often more stable in vacuum than the metal which they coat. Nonporous stable coatings should provide substantial protection to the underlying material unless the temperature is so high that diffusion through the coating is appreciable. Porous coatings are likely to be undermined and detached by loss of underlying material through the pores. Even porous coatings may, however, be of some help when a very small amount of undesirable loss would otherwise occur and redeposition on cold electrical surfaces is a problem.

C. Loss of Organic Materials in Vacuum

Most of the organic materials used in spacecraft are long-chain polymeric compounds which degrade in a vacuum not by evaporation or sublimation but by breakdown of the compounds into smaller, more volatile fragments. The molecular weight of these fragments is not well established; neither is the equilibrium decomposition pressure of most polymers. Accordingly, the Langmuir equation is not usually useful for the organic materials of interest, and it is necessary to turn to direct experimental studies of the weight loss of polymers in vacuum.

A number of such studies have been made which vary considerably in the care in which the work was done and the pertinence of the tests to space conditions. Good work has been done over the past dozen years by chemists interested in the kinetics of vacuum pyrolysis of high polymers; the contributions of Madorsky,

Wall, Straus, and their colleagues at National Bureau of Standards deserve particular mention (30-47). In this work the weight loss of small samples of pure well-defined polymers was measured as a function of both time and temperature in vacuums of 10^{-6} mm; the times ran from 1/2 to 48 hr. Information on vacuum exposure for times of a year or more is limited to a very few materials built into laboratory vacuum systems or into spacecraft, held at one temperature, and observed on a go/no-go basis only. Accordingly, it is worth while to attempt to obtain more information by extrapolating the short-time data to longer periods. As the measured curves of weight loss vs time are usually nonlinear (Fig. 1), extrapolation of such curves is risky. A better approach is to plot the time t for a given weight loss of interest vs the temperature. Plots of measured log t vs 1/T are usually close to linear (Fig. 2), as would be expected from theory (29). Though extrapolation of log t vs 1/T plots involves some risk, the risk is much less than for the nonlinear plots of weight loss vs time. Those measurements made as functions of both time and temperature have been extrapolated in this way and are given in Table 4 as A quality data.

Such measurements have not been made on all polymers of practical interest, however. For a larger number, more limited data are available. In Table 4, qualities B and C denote measurements of weight loss vs temperature at one fixed time; B with high-purity well-defined polymers; C with commercial plastics or elastomers. The quality D denotes measurement of weight loss or other properties at one elevated temperature only, while E denotes measurements of pressure change in a laboratory vacuum system at an elevated temperature. These measurements were used only as a relative indication for interpolation of

- 11 -

additional materials between the polymers for which A quality measurements were found; in Table 4, temperatures assigned for the B-E measurements are also by interpolation. Thus Table 4 gives an estimated order of merit for behavior of polymers in vacuum together with temperatures where the estimated weight loss is 10% per year. These temperatures are subject to considerable uncertainty; designers are urged to be conservative in using them. When a single temperature is given for a material in the table, this often means that only one determination was found in the literature. It does not mean that the material is less variable than those materials for which a range of values is shown.

Inspection of Table 4 shows considerable scatter in temperature for most kinds of polymer. One reason is that the designations refer to polymers made from whole classes of monomers; they could be subdivided further by the particular monomer or monomers used. The chain length (molecular weight), branching, and cross-linking of the polymer have some effect upon decomposition. Moreover, the data indicate that the rates of decomposition in vacuum are often greatly accelerated by small amounts of impurities and addition agents. In particular, the catalysts which are ordinarily used to induce polymerization of the monomer also, if left in the polymer, commonly catalyze decomposition of the latter. Many polymers can be made without catalysts or the catalysts removed after polymerization, but this is difficult and not the usual commercial practice. Plasticizers and mold lubricants, used to help fabrication and to modify mechanical properties are also highly detrimental to stability in vacuum. Certain degradation inhibitors may increase vacuum stability, although antioxidants are clearly of no use. The particular formulation and curing procedure used may,

therefore, have important effects upon vacuum stability. Accordingly, wide variations in behavior may be expected for any particular type of polymer. Trade names, too, mean little in this field; they serve to identify the manufacturer but often do not even define the type of polymer. Thus the measurements are useful only as a general guide; for careful work, experiments are needed with particular formulations and curing procedures of interest.

The reader may wonder why the values in Table 4 are given in terms percent weight loss per year rather than as a loss of thickness per year. Since the process is not one of evaporation or sublimation but of decomposition, it takes place not at the surface but throughout the volume of the piece. Moreover, measurements indicate that, at least in thicknesses up to 0.12 cm (0.050 in.) and times up to 48 hr (40, 52), the loss does not depend on the surface area but on the total volume or weight; apparently the decomposition itself is the rate-limiting process rather than diffusion of the decomposition products out of the solid. For sufficiently thick samples, diffusion will limit weight loss and the percent loss in a given time will fall somewhat (30, 66, 67); however, the accompanying degradation in properties may not be retarded. The effect of time on the rate controlling process has not been determined; at long times degradation seems likely to be more important than diffusion.

it should be noted that Tables 2-4 do not imply that the materials are usable at the temperatures listed. These tables pertain only to rates of sublimation or decomposition in vacuum; processes which occur in the same way in both air and vacuum, such as loss of strength with increasing temperature, may limit the usefulness of the material and are not discussed here. Polymers are

commonly more stable at elevated temperatures in the absence of oxygen (68).
In many cases the upper temperature limit for useful service in air is lower than
that indicated in these tables and probably will be used to govern design for
vacuum as well.

Coatings may be put over organic materials to reduce their net rate of
breakdown in vacuum (48). The coating prevents degradation products from leav-
ing the underlying material and permits them to recombine to some extent. Either
organic or inorganic coatings may be used.

Organic materials of very short chain length, such as oils and the greases
based upon them, are not covered by Table 4. For these materials, loss in
vacuum occurs primarily by evaporation. The chain length (molecular weight)
has a major effect on the vapor pressure and evaporation rate of oils; the evapor-
ation rate decreases as the molecular weight increases because of the accompany-
ing sharp drop in vapor pressure. As a result, oils cannot be ranked in order of
volatility by chemical type alone. These materials are often of sufficiently low
molecular weight that they evaporate without decomposition; the Langmuir equa-
tion (Eq. 1) can then be used to calculate rate of loss from vapor pressure data.
Many commercial oils are mixtures of various molecular weight compounds;
some components may evaporate out of the mixture while others remain.

If organic materials are used in partial enclosures containing temperature
gradients and exposed to vacuum, there is a possibility that they, like inorganics,
will evaporate or decompose to volatile products in the warmer areas and that
the volatiles will redeposit on the cooler surfaces. If the cooler surfaces must
conduct electricity or heat this may lead to malfunction. In particular, oils and

plasticizers (discussed below), can redeposit on exposed relay contacts and prevent them from closing properly (69).

D. Property Changes of Inorganic Materials

There seems to be no good evidence of any important decrease in mechanical properties of inorganic materials in vacuum, as compared to their properties under the atmospheres in which they are ordinarily used, provided the temperature is not so high that appreciable sublimation occurs. In fact, properties are usually better in vacuum because of freedom from corrosion(70). An exception may occur under elevated temperature conditions for a few materials where an in-air advantage is taken of internal oxidation to strengthen the material (60).

Likewise, the optical properties should not be affected if the temperature is low enough to avoid sublimation and change of composition. This last point may bear watching, both for alloys containing volatile elements and for ceramics to be used at high temperatures. Rather small losses of oxygen and perhaps of nitrogen, which may occur in vacuum at high temperatures, may be sufficient to change appreciably the emissivity of some ceramics. Also, some ceramics, particularly oxides, are hydrated; loss of water may occur in vacuum, with resulting emissivity changes. A possible case, on which no experimental work seems to have been done, is the hydrated aluminum oxide coating put on aluminum metal by the anodizing process. Related is the situation where a metal readily forms a thin oxide coating on exposure to air but the oxide is volatile or unstable in vacuum. Nickel would be an example; its emissivity may be different in space than in air.

Electrical properties, also, will be generally affected by vacuum only if sublimation or composition changes occur. Slight losses of oxygen, nitrogen, and water may affect resistivity and other properties of ceramics.

If uneven sublimation occurs, some properties may be more affected than if the sublimation is uniform. Thus it is possible, though not confirmed, that the accelerated sublimation of grain boundary material will introduce surface notches which lower resistance to crack propagation under conditions of rapid or repeated loading. Surface roughening resulting from grain boundary sublimation and from differences in sublimation rates and direction in different grains of the microstructure can decrease optical reflectivity and increase optical emissivity and absorptivity (71). This can be important both for conventional optical components and for the temperature control surfaces which, by establishing the radiation balance, maintain spacecraft temperatures within prescribed limits.

E. Property Changes of Organic Materials

It is possible, in principle, for internal chemical changes to occur in organic materials exposed to vacuum which would affect the properties of the material without appreciably changing the weight. There seems to be little good evidence, however, that detrimental property changes occur in practice without weight loss, except at temperatures where detrimental changes also take place in air. When weight loss occurs, it may be accompanied by significant changes in mechanical, electrical, and optical properties, as well as in dimensions. Few quantitative data on these changes are available; if detailed information on a particular property of a particular material is required, it is usually necessary

at present to test the property experimentally. In general, however, it may be said that weight losses of 1 or 2% do not produce property changes of engineering importance, but that weight losses of 10% are accompanied by considerable changes in engineering properties (53, 55). It is for this reason that 10% weight loss per year was chosen as a criterion in Table 4.

An exception to the above general statement must be made for plastics and elastomers containing plasticizers which are volatile in vacuum (71). In some cases, losses of less than 10% of plasticizer from a plasticized polymer may be enough to embrittle the material significantly (72). For this reason, again, plasticized materials, particularly those containing so-called "external" plasticizers, should generally be avoided for space applications.

A special kind of damage may occur to foamed polymers in vacuum. The walls of closed cells in the foam will be subject to internal pressure when the foam is in vacuum and may break. This may have some effect on the mechanical behavior of the foam.

F. Diffusion of Gases Through Containers

There has been some concern about the loss of gases through container walls into the vacuum of space. The rate of diffusion through a metallic or non-metallic wall, however, varies approximately directly with the pressure differential across the wall. The pressure differential will be only 1 atmosphere greater in space than on Earth. A pressure vessel holding gas at 100 atmospheres (gage) will be subject to 101 atmospheres pressure differential in space, so the loss rate will be 1% greater in space than on Earth. A pressure vessel

sealed at atmospheric pressure will lose gas in space at the same rate as would the same vessel holding 2 atmospheres on Earth. Thus if a container will hold gas on Earth, it will hold gas in space, unless the container is made of a material that sublimes or degrades in space.

G. Friction and Lubrication

Friction, wear and lubrication may well constitute the greatest materials problem for successful operation in space.

Lubrication techniques are usually divided into hydrodynamic lubrication and boundary lubrication. Hydrodynamic lubrication consists of maintaining a continuous fluid layer between the solid surfaces that move over one another, with the fluid exerting sufficient pressure to keep the solid surfaces from touching. Hydrodynamic lubrication provides very low coefficients of friction and essentially no wear. It is often not practical for the designer to insure hydrodynamic lubrication on Earth, it is more difficult to do this in space, where vacuum may make retention of the fluid a problem and resupply is less simple. If hydrodynamic lubrication can be maintained, it will work as well in space as on Earth.

Boundary lubrication means that the solid surfaces touch, though usually only at some microscopic irregularities. A liquid lubricant may or may not be present, but does not prevent solid contact. Some wear occurs, and friction is generally higher than with hydrodynamic lubrication, but boundary lubrication is easier to maintain. On Earth, exposed solid surfaces quickly adsorb films of oxygen and water vapor. The surfaces are thus "dirty" and the "dirt" acts as a lubricant and plays a major part in reducing friction under conditions of boundary

lubrication. When surfaces are clean and free from adsorbed films of atmospheric gases, they commonly tend to weld to each other on contact; wear rates and coefficients of friction are then very high (73-75). Cleaning of surfaces in space takes place by loss of adsorbed gases into the vacuum; sputtering by protons hitting the surface, which will be discussed later, accelerates this process. With some metals, the adsorbed gases may also dissolve in the metal and diffuse into it, leaving the surface clean; with others, carbon originally dissolved in the metal may diffuse to the surface and react with the adsorbed oxygen or water to form carbon monoxide, which is less strongly adsorbed (76). Mechanical wear between mating surfaces provides another mechanism of cleaning. Once the surfaces are clean of adsorbed oxygen and water, they will tend to stay clean in space.

The most promising approach for lubrication in space is to reduce exposure of the contact area to the vacuum. A vacuum-tight seal around all the moving parts provides maximum protection. If moving parts must extend into the vacuum, a vacuum-tight shaft seal may be used for low-speed service, but at the expense of frictional losses and wear at the seal. For high speed but low loads, a magnetic drive can be used to pass motion through the solid wall. If the wall is metallic, some eddy-current losses will result but no wear at the wall; some bearings outside the wall will be needed. If these techniques of keeping an atmosphere around critical bearings or gears are impractical, even a less perfect enclosure, such as that provided in an ordinary so-called "sealed bearing," will greatly increase the life of a bearing or gear train in vacuum. If the opening in the enclosure is smaller than the surface from which loss takes place,

the rate of loss of lubricant or atmospheric gases will be approximately proportional to the opening seen by the surface. Under this condition, an enclosure of 99% of the solid angle, leaving 1% cracks, should delay failure by a factor of roughly 100.

Low vapor pressure oils and greases are obviously advantageous for vacuum lubrication. Some low vapor pressure oils and greases--silicone base, petroleum base, and ester base--have lubricated high-speed ball bearings successfully for several thousand hours in vacuums of 10^{-5} to 10^{-6} mm of mercury (77-79); longer tests have not been reported. Not all materials of these types have good performance as boundary lubricants in vacuum; commercial products of the same general type vary widely, depending on exact composition and molecular weight. Indeed, many low vapor pressure oils do not have good lubricity even in air; this is particularly true of some silicones. Load-carrying capacity of petroleum oils is usually reduced at low pressures (80); also, low vapor pressure petroleum oils generally have a high pour point and are, therefore, unsuitable for use at low temperatures (81). Most of the available low vapor pressure oils of all types have evaporation rates of the order of 10^{-4} g/cm^2-hr (77) or 10^0 cm/yr; this may be intolerably high for long-time service in space unless some form of enclosure or resupply is provided.

A problem with oils and greases in high vacuum may arise from the tendency of oils to creep over clean surfaces and reach areas where they are not desired; this behavior may also increase the evaporation rate by increasing the surface area. The creeping tendency of oils in high vacuum may be controlled by use of nonwetting (69) or absorbant surfaces or by proper geometry. Another

factor which should be considered is the tendency of clean metal surfaces to catalyze polymerization of oils into gums and varnishes (69). When the oil or grease contains dissolved air or water, or air bubbles, or a volatile fraction, rapid expansion of this entrained volatile material as the pressure is reduced may force much of the lubricant out of the bearing (69). Because heat transfer tends to be poor in the absence of air, as will be discussed later, oils and greases which are satisfactory in a device operating in air may get too hot for proper functioning when the device is operated in vacuum. In space there is also increased difficu'ty of resupply of lubricant because of long-time unattended operation and the absence of gravity.

Fatty acids, such as stearic, lauric, and palmitic acids, are sometimes added to oils to reduce friction and wear in boundary lubrication. The effect of these acids depends upon chemical reaction with the metal surfaces to form metallic soaps; this reaction requires the presence of oxygen and water. In vacuum, accordingly, because of a lack of significant amounts of oxygen and water vapor, fatty acids do not give low friction and wear, although they do prevent seizing (74, 75).

Solid lubricants, because of their generally lower vapor pressures, will suffer less loss by evaporation than liquid lubricants (oils and greases). On the other hand, a solid coating tends to wear away, and is not replaced by flow as a liquid is. Properly selected solid lubricants have been used in vacuums of 10^{-5} to 10^{-6} mm for times up to 1000 hours or so.

Among the solid lubricants, graphite is useless in a vacuum; in the absence of adsorbed water films it acts as an abrasive (82, 83). Molybdenum

disulfide (84, 85) and plated metal films can be used. However, results reported with molybdenum disulfide vary widely; it appears that the method of applying the sulfide to the surface is most important. Molybdenum disulfide bonded with silicone, phenolic, and epoxy resins, and with colloidal silica, has given lives of some hundreds of hours in vacuum as a coating on ball and sleeve bearings running at very high speeds and light loads (79, 86, 87); with a sodium silicate bond, lives up to 2000 hours have been obtained (79). The surface finish and preparation of the underlying surfaces apparently must be good, and clearances between mating parts must be adjusted to compensate for the thickness of the film and lack of fluid lubricant. Film thicknesses of 4 to 12 microns (0.15 to 0.5 mil) seem best (79). Particle size of the molybdenum disulfide is probably also important. Molybdenum disulfide can also be applied by impregnation in porous metals or as a filler in plastics. A bearing coated with molybdenum disulfide should have a carefully controlled run-in period, starting at low speed and gradually increasing the speed, with loosened fragments of the sulfide being blown out at intervals during this period (79).

Thin platings of silver (88), gold (89, 90), or barium (91), usually applied by evaporation on to harder substrate, and operating against harder metals, have also been used satisfactorily; they are standard for rotating anode X-ray tubes where high-speed rotation at 10^{-6} mm of mercury must be provided for 1000 hours or more. Clearances and finishes are again critical. To insure good adherence of the soft metal film to the substrate, careful cleaning and plating techniques are required. The plating thickness must be carefully controlled; the friction coefficient is a minimum for thicknesses of a few thousand angstroms

(around 10^{-5} in.) (79), but thicker films would give longer wear life. These coatings, all quite thin, are easily damaged in handling; also, they do not work well in air and so are not suitable for parts which must operate both on Earth and in space. This may be a limitation if the parts must be tested on the ground before flight. Clauss (92) has suggested that it may be possible to protect silver and gold films with a compatible oil during ground testing; many lubricating oils, however, contain chlorine or sulfur compounds which would rapidly corrode the films.

An unlubricated metal running against a part of the same metal usually seizes quickly in vacuum, although some metals have been run for short times at very low loads and speeds at 10^{-5} to 10^{-6} mm Hg (92). If the two parts are of different metals, and have little solid solubility in each other, seizure is much less likely, although the coefficient of friction will still be high (94, 95). Very little experimental work has been done on this subject; tantalum and tungsten have been successful and iron moderately successful against copper in vacuum under mild conditions only (94); other promising combinations, such as steel against bearing bronze, thick sections of silver, or babbitt, have apparently not been tested in vacuum.

Sliders of aluminum oxide (sapphire) operating against soft austenitic stainless steel or copper have been reported to work without seizing at 2×10^{-7} mm Hg in slow intermittent use over long periods (79). The coefficient of friction of sapphire and diamond on themselves and on metals is high in vacuum, however; metals tend to seize to diamond (75, 96). There seems to be little

- 23 -

experimental basis for the often-expressed opinion that jewelled bearings should work well in vacuum.

Tetrafluoroethylene vs itself or vs steel has been used successfully in vacuum, at least down to 10^{-6} mm Hg (97). This soft material may be reinforced with glass fibers to increase strength and reduce deflection, and may be impregnated with molybdenum disulfide. It may also be used as an impregnant in porous metals. A tetrafluoroethylene retainer has been successfully used to lubricate steel balls running against steel races for long times at 10^{-6} mm (98). Friction between plastics other than tetrafluoroethylene is higher in vacuum than in air; it is not known whether they seize when clean. As mentioned above, the stability in vacuum of many of these plastics, such as nylon, is questionable.

As will be discussed shortly, in order to simulate space vacuum properly in laboratory studies of friction and lubrication, pressures of 10^{-9} mm Hg or lower should be used. In no case to date has this been done. Accordingly, laboratory data indicating that any method of boundary lubrication will work in space must be taken with some reservation. The small amount of data available on operation of moving parts in space, except for times no longer than a few minutes after launch, will be covered in the concluding section of the paper.

H. Heat Transfer

A difficulty which is not strictly one of materials but is related to materials problems sometimes arises with respect to heat conduction across faying (statically touching) surfaces. In air, a large part of the heat transfer across faying surfaces occurs by conduction through a very thin air film separating the

- 24 -

two solid surfaces. In vacuum, with the air film absent, heat transfer must occur by conduction through the small area of asperities that are actually in solid-to-solid contact and radiation across the thin vacuum space separating the two solids; this is considerably less efficient. As conductive and convective heat transfer by air at other exposed surfaces is also absent, heat transfer may be a serious problem. To increase transfer across faying surfaces, a soft layer of conductive material, such as copper foil, may be interposed and the parts mounted with compression between them to eliminate voids. Alternatively, a grease with low vapor pressure may be used to provide a thermally conductive path between the two solid surfaces.

I. Laboratory Simulation of Space Vacuum Conditions

When for laboratory studies of sublimation and decomposition it is desired to simulate the vacuum of space, conditions should be such that every molecule of the material which leaves a surface will stay away, and not come back. It is not necessary, or even advantageous, to have the air pressure in the system as low as in space. If the air pressure in the system is 10^{-5} mm Hg or lower, the mean free path of vapor molecules between collisions with each other and with air molecules will be several meters or more. Thus, collisions in the gas will rarely occur. Molecules of a material can then come back to the test surface only by condensing on the walls of the vacuum system and then resubliming. This can be prevented by keeping the walls cold compared to the specimen, so that the rate of sublimation from the walls is negligible.

For heat transfer studies, 10^{-5} or even 10^{-4} mm Hg is enough to make heat transfer by air conduction and convection small compared to heat transfer by radiation.

For lubrication and surface property studies, on the other hand, when space conditions are simulated, air molecules should be prevented from reaching the contact surfaces and building up monomolecular and thicker layers of adsorbed atmospheric gases. This requires that the air pressure be considerably lower than is usual in laboratory vacuum systems. At 10^{-6} mm Hg, which is considered a good laboratory vacuum, molecules reach an exposed surface so fast that even if the surface is initially clean, a monomolecular adsorbed air layer will build up in less than 2 sec. At 10^{-9} mm Hg, however, it will take 25 min for an air monolayer to build up on a clean surface, which may be long enough to carry out the experiment (53). This pressure is about at the limit of the present state of high-vacuum art under conditions where the specimen of interest may be evolving gases and is commonly of a composition that cannot be baked out at high temperatures to clean it. Again, cold walls should be used to prevent return of evaporated material.

Because gas evolution plays an important part in the behavior of materials in vacuum, pumping systems which can cope with evolved gases are essential. Pumps which provide high pumping speed at appropriate pressures are therefore needed; ability to produce low ultimate pressure in a clean system is of little importance. Diffusion pumps should be provided with traps cooled by liquid nitrogen to prevent pump oil from diffusing or creeping back into the test chamber.

IV. EFFECTS OF IMPINGING ATOMS, IONS, AND ELECTRONS

The behavior of materials in space may be affected not only by the absence of particles--the vacuum-- but also by the presence of particles which impinge on the material. Of these particles, gas atoms and their ionization products--electrons and ions--will be considered first.

A. Atoms, Ions, and Electrons in Space

Nearest the Earth, a satellite will undergo collisions with the atoms of the Earth's upper atmosphere. The lower the satellite is, the more collisions it will have with these atoms. The worst case is for a satellite at minimum altitude, say 200 km (125 miles). Here the number of atoms is approximately $10^{10}/cm^3$ (Table 1), and the velocity of the satellite relative to the Earth is about 7.4 km/sec. Thus about 10^{16} atoms/cm^2-sec will be swept out by the satellite. A nitrogen or oxygen atom striking at 7.4 km/sec has a kinetic energy of 4.3 ev; the energy of random thermal motion corresponding to the atmospheric temperature of 10^3 °K (Table 1) is negligible compared to this.

The inner Van Allen radiation belt of the Earth starts at 400 to 1200 km (250-750 miles), depending on the longitude. It extends up to about 10,000 km (6000 miles) altitude, where it begins to overlap the upper belt. The inner belt extends from about 45 deg north magnetic latitude to 45 deg south magnetic latitude (Fig. 3). In the region of highest intensity, altitude of about 3600 km (2200 miles) at the magnetic equator, the flux of protons with energies over 10 Mev is between 3×10^4 and 2×10^5 proton/cm^2-sec. About 1×10^4 to 4×10^4 proton/cm^2-sec have energies above 40 Mev, and probably about 10^2 proton/cm^2-sec

have energies above 650 Mev. No protons have been found above 700 to 1000 Mev.
There are no data on protons with energies below 7 Mev (99-101, 103-109). The
proton flux above a given energy in the range of 80 to 450 Mev varies as the
-0.84 power of the energy in the lower portion of the belt (104, 107, 110). If in
the absence of data this relationship is assumed to hold to lower energies, the
proton flux above 20 kev would be about 10^7 proton/cm^2-sec, and above 1 kev
would be about 10^8 proton/cm^2-sec. Extrapolation of the flux to lower energies
on the same basis would imply too high a proton concentration to be consistent
with other data. The highest electron flux measured in the inner zone is about
3×10^{10} electron/cm^2-sec, within a factor of 10, at energies of above 20 kev.
Perhaps 10^{10} electron/cm^2-sec have energies above 100 kev, and there are 10^7
electron/cm^2-sec, within a factor of 2, above 600 kev. Less than 10^5 electron/
cm^2-sec have energies above 1 Mev. There are no data on electrons with energies
below 20 kev (99, 100, 103, 108, 111). The flux is strongly directional, with most
particles moving perpendicular to the local magnetic field (112).

The outer Van Allen belt starts at about 10,000 km (6000 miles) altitude
near the magnetic equator and extends out to 60,000 to 85,000 km (40,000-55,000
miles) altitude, depending upon solar activity; peak intensity is at 16,000 to 23,000
km (10,000-14,000 miles) altitude at the equator (Fig. 3). At higher latitudes
the zone is closer to the Earth, intersecting the atmosphere at magnetic latitudes
of 50 to 70 deg, where it causes aurorae; the peak flux falls off as latitude increases.
The outer belt, like the inner, does not extend over the Earth's poles (99, 106,
108, 113). The outer zone is greatly influenced in both extent and intensity by

solar storms; the intensity may change by a factor of 10 at the peak and by a factor of 100 beyond the peak. A typical electron flux at the peak is 10^{11} electron/cm^2-sec at energies above 20 kev. About 10^4 electron/cm^2-sec are at energies above 1.5 Mev; about 1 electron/cm^2-sec above 4.5 Mev (Fig. 4). Essentially no data exist for electrons below 20 kev (99-103, 106, 113-118). The electron flux appears to be directional: essentially normal to the local magnetic field (112). There is so far no evidence of energetic protons in the outer zone; the number above 30 Mev is less than 1 proton/cm^2-sec (108, 114).

There have also been suggestions of a "ring current" of low-energy particles about the Earth. However, the authors who have proposed this disagree completely as to the nature and position of the ring current (119-123).

Beyond the radiation zones, solar emissions and cosmic rays are present. Solar flares occur about once a month at the maximum of the 11-yr solar period and perhaps 1 or 2 per year at the solar minimum. The proton flux near the Earth associated with a major flare is typically 10^4 proton/cm^2-sec at energies above 20 Mev, extending up to 10^2 proton/cm^2-sec above 100 Mev and 10^0 proton/cm^2-sec above 500 Mev. Record flares, occurring perhaps twice each solar maximum, have had proton fluxes 10 times as great. The proton flux accompanying a solar storm usually lasts about a day (101, 103, 108, 124-136).One measurement after a flare of moderate size showed 10^6 to 10^7 electron/cm^2-sec at roughly 50 kev (137).

The energetic solar flare protons do not extend below a threshold of about 20 Mev. There are also low-energy flare protons at 1/2 to 20 kev; the flux of these is not well known. It may be lower than 10^8 proton/cm^2-sec at solar

minimum (138) and possibly as high as 10^{12} proton/cm^2-sec at solar maximum (139). Low-energy electrons, at 1/4 to 10 ev, presumably accompany the low-energy protons; their flux may be 1 to 40 times the proton flux.

There is also believed to be a steady solar output of protons amounting to less than 10^9 proton/cm^2-sec near the Earth's orbit. Their energy is less than 3 kev and probably less than 1/2 kev (3, 5, 8, 9, 16, 124, 139-143). The proton direction is probably almost radially outward from the Sun, but it may possibly be random. Accompanying the protons are probably heavier ions in the concentrations found in the solar atmosphere: about 15 atomic percent He, 10^{-1}% O and C, 10^{-2}% N, Si, 10^{-3}% Mg, S, Fe, and smaller amounts of other ions (144). The necessary electrons to neutralize the positive particles may be present in a flux as high as a few times 10^{10} electron/cm^2-sec but at energies probably below 2 ev; their direction is probably random.

The cosmic ray flux near the Earth's orbit varies from 1 particle/cm^2-sec at solar maximum, all above 1 Bev, to 3 particle/cm^2-sec at solar minimum, all above 100 Mev. About 10^{-1} particle/cm^2-sec are above 10 Bev; the flux above a given higher energy varies as the -1.25 power of the energy, and extends up to 10^{19} ev (103, 108, 145). The protons are accompanied by about 13% alpha particles and 1% heavier ions (128). The electron component above 1 Bev is less than 1% of the proton flux (146).

B. Sputtering in Space

When atoms or ions with energies ranging from about 10 ev to perhaps 1 Mev strike a solid or liquid surface, they tend to knock atoms off the surface.

This may increase the loss over that occurring in a vacuum. This process is called "sputtering." There are major uncertainties both in the flux of atomic particles to which a spacecraft might be exposed and the rates of sputtering by a given flux of particles. It is nevertheless possible to make order-of-magnitude estimates of possible sputtering effects.

For a low Earth satellite, collisions with the atoms of the Earth's upper atmosphere might cause some sputtering. At minimum altitudes, a satellite will strike about 10^{16} atoms/cm^2-sec of nitrogen and oxygen at an average energy of 4.3 ev. The sputtering efficiency (number of atoms sputtered off a surface per incident atom or ion) for nitrogen or oxygen atoms at 4.3 ev is believed to be less than 10^{-10} (147). Thus less than 10^6 atoms/cm^2-sec or 10^{13} atoms/cm^2-yr will be removed from the surface by sputtering. With an average atomic volume of about 5×10^{-24} cm^3, the loss of thickness would be less than 10^{-10} cm/yr or 10^{-2} Å/yr--completely negligible.

In the radiation belts, bombardment by protons and heavier ions must be considered. At the time of writing, unfortunately, measurements are limited to proton energies well above 1 Mev. Extrapolation gives 10^8 proton/cm^2-sec as the number above 1 kev, at the peak of the inner belt. The sputtering efficiency of these protons is about 0.1 or lower (147-152). Multiplying the extrapolated flux by this sputtering efficiency gives a loss of 10^7 atoms/cm^2-sec, or about 0.1 Å/yr. This again would be neglibible.

For the outer radiation belt, there is no evidence even of the existence of protons at 10 ev to 1 Mev.

- 31 -

The flux of solar flare protons at 1/2 to 20 kev is very uncertain; estimates range from 10^8 to 10^{12} proton/cm^2-sec. The sputtering efficiency would be 0.01 to 0.2 (147, 151), so the loss would be less than 2×10^{11} atoms/cm^2-sec at the height of an emission. At 10^6 sec of high emission per year, this adds up to a maximum of 2×10^{17} atoms/cm^2-yr, or 100 Å/yr, again negligible.

Steady solar proton emission will give rise to a flux on a spacecraft of not more than 10^9 proton/cm^2-sec. The proton energy is believed to be between 1 ev and 3 kev. At the lower energies no sputtering would occur; at the higher, with a sputtering efficiency of 0.3, the maximum rate would be 3×10^8 atoms/cm^2-sec, or about 3 Å/yr: negligible for any application.

Cosmic rays will not cause significant rates of sputtering because of their high energy and low flux.

From the age of meteorites, as measured by isotope analysis, several authors (153-156) have calculated that the over-all erosion rates, when the meteorites were in interplanetary space, were less than 30 Å/yr, and probably less than 1 Å/yr. This provides order-of-magnitude confirmation of the above sputtering estimates for the region beyond the radiation belts.

C. Radiation Damage in Space Environment (General)

Energetic atomic particles can cause radiation damage, as is well known. Protons and electrons of a given energy penetrate and do their damage to a definite depth or range in materials, commonly expressed in terms of the g/cm^2 through which they will penetrate; the higher the particle energy, the greater its range will be. The proton range also varies approximately as the square root of

the atomic number of the material. For electrons, the nature of the material has little effect on range, except that the range in hydrogen is about half that in other materials. Electron ranges are greater than those of protons of the same energy. When fast electrons interact with matter, a small percentage produce X-ray photons, which may have energies up to that of the electrons. This process, called "bremsstrahlung," is important because the photons may also cause radiation damage, and their range in matter is much greater than the range of the electrons producing them. Photons of a given energy do not all stop at any definite depth in matter; rather, their number falls off exponentially with distance. The photon range is defined as the g/cm^2 at which the photon flux is reduced by a factor of $\underline{e}$ (base of natural logarithms). Photon range decreases with increasing atomic number.

Radiation damage occurs primarily through two mechanisms: ionization and atomic displacement. Ionization, removal of electrons from the atoms of the material, is the chief mechanism of damage to insulators: plastics, elastomers, oils and greases, glasses, and ceramics. Almost all of the energy of fast protons and electrons and of bremsstrahlung photons ends up as ionization when these particles interact with matter; so the total amount of ionization is determined by the amount of incident energy. Because of their lower range, low-energy particles distribute the ionization over a smaller volume of material and so cause more intense radiation damage than an equal flux of high-energy particles. Ionization is commonly expressed in erg/g. Biologists use such ionization units as roentgens and reps (83-93 erg/g) and chemists sometimes use rads (100 erg/g).

Radiation damage to metals and semiconductors is primarily due to the second mechanism: atomic displacement. Displacement is also important in inorganic insulators, such as glasses and other ceramics. Displacement consists of atoms knocked out of their positions in the crystal lattice by collisions with the incident particles, directly or indirectly. The intensity of displacement production falls with increasing proton energy but rises with increasing electron energy. Displacements are conveniently expressed as the fraction of atoms displaced.

The energy threshold for ionization is about 20 ev for electrons and photons and 1000 A ev for protons, where A is the atomic weight of the atoms ionized. The energy threshold for displacement is about 8000 A ev for electrons and photons and 7 A ev for protons. For particles below these thresholds, radiation damage does not occur. As the thresholds suggest, electrons and photons tend to produce much less displacement than protons, and so are less likely to damage metals and semiconductors.

Detailed information on ranges and amounts of ionization and displacement produced by protons, electrons, and photons of various energies in a number of materials is available in many publications (157-166) and will not be repeated here. If the particle fluxes and energies encountered in various regions of space, as described above, are combined with these data, Table 5 can be constructed. This table shows the ionization and displacement doses which will be produced by the protons and electrons at the peak of the inner radiation belt, by the electrons at the peak of the outer radiation belt, by both energetic and low-energy solar flare protons and electrons, by the protons and electrons of the steady solar emission, and by cosmic ray protons. Doses are tabulated for the exposed

surface, through 1 mg/cm^2, and through 1 g/cm^2. The doses given vary somewhat with the material exposed, but generally not by more than an order of magnitude; only orders of magnitude are given. The greatest uncertainties arise from lack of information as to the energy and flux of the lowest energy particles in the inner radiation belt and in the solar flare and steady emissions. These particles of very low range may deliver very high ionization and, especially, displacement doses to exposed surfaces, but because of the presence of thresholds the doses depend critically on the still unknown particle energies. The results of Table 5 are summarized in Table 6; here all types of solar corpuscular radiation are lumped together.

D. Radiation Damage to Specific Materials

There is a great deal of data in the literature on the effects of radiation on the mechanical, electrical, optical, and other properties of many materials of engineering interest, such as plastics and elastomers (164, 167-178), oils, and greases (179-181), glass and fused silica (182-198), inorganic crystalline insulators (160, 163, 187, 192-194, 197-204), semiconductors (118, 160-163, 197, 205-212), and metals (160, 163, 213-215). Most of this information, however, was obtained in connection with nuclear reactor studies, in which the incident particles of interest are neutrons and gamma rays rather than protons and electrons. It is possible to utilize many of these data for evaluation of radiation damage in space, if one realizes that gamma rays produce mostly ionization and fast neutrons produce mostly displacements. One roentgen, rep, or rad is equivalent to an ionization of approximately 1 x 10^2 erg/g. One reactor fast neutron displaces about 10^{-22} of the atoms/cm^2 along its path (160, 161). Table 7, which shows the amount of ionization or displacement that will produce appreciable

change in engineering properties of various materials, was prepared in this way.
Within a given class of material, such as glass or plastics, the sensitivity of
individual materials to radiation may differ by several orders of magnitude;
details may be found in the references cited. Likewise, for a given material,
individual properties of a kind, such as different mechanical properties, may
differ in their sensitivity to radiation.

If the information in Tables 6 and 7 is combined, one obtains Table 8,
which indicates the expected damage to various materials by the radiation belts,
solar emissions, and cosmic rays, and shows that near the peak of the inner
radiation belt, exposed surfaces of most materials may suffer major changes in
engineering properties, generally in much less than a year. The possible excep-
tions are metals and crystalline ceramics, whose mechanical and electrical
properties may or may not be affected. In non-metals, these changes will extend
to a depth of 1 mg/cm^2 (typically 1 to 10 microns or 0.04 to 0.4 mil) or more,
but for me' is only ferromagnetism will be affected at this depth. Through walls
of 1 g/cm^2 (typically 0.1-1 cm or 0.05-0.5 in.), the usefulness of semiconductor
devices depending on minority carrier effects will probably be affected within a
year, as will that of many polymers and optical materials. Lubricant properties
and the mechanical and electrical properties of metals and inorganic insulators
should remain unaffected, except that sensitive insulators may show a temporary
increase in conductivity during exposure.

Near the peak of the outer radiation belt, the properties of organics and
of optical materials will, again, probably be seriously changed within a year to
a depth of 1 mg/cm^2 or more. Minority carrier phenomena in most semiconductors

will be affected, as will the electrical and mechanical properties of most inorganic insulators. Metals will be unaffected. Through 1 g/cm^2, the more sensitive polymers and optical materials will probably be damaged, but the less sensitive will not. Inside 1 g/cm^2 of shielding, semiconductors, lubricants, metals, and the mechanical and electrical properties of inorganic insulators will be unaffected, except that a temporary increase may occur, during exposure, in the electrical conductivity of sensitive insulators and in the number of minority carriers in semiconductors.

Beyond the outer radiation belt, solar radiation effects are predominant. Effects on exposed surfaces are hard to judge because of our poor knowledge of low-energy solar proton and electron emission, but these surface effects may be serious for most materials. Even 1 mg/cm^2, however, will shield out most of the low-energy particles. Thus, through this thickness, only the minority carrier properties of more sensitive semiconductors, optical transmission of some glasses, and the more sensitive polymers are likely to be permanently damaged. The polymers will not suffer this damage if inside 1 g/cm^2. A temporary increase in electrical conductivity of insulators may occur while they are exposed to solar flare emissions.

Cosmic rays will not cause any radiation damage even over periods of years.

V. EFFECTS OF ELECTROMAGNETIC RADIATION

A. Electromagnetic Radiation in Space

Among the particles in space that can affect materials are photons--that is, electromagnetic radiation. The Sun is the primary source of electromagnetic radiation in the solar system. The intensity of this radiation varies inversely as the square of the distance from the Sun. At the Earth's mean distance (1 astronomical unit or AU), the total solar electromagnetic energy flux is 1.40×10^6 erg/cm^2-sec or 0.140 watt/cm^2, ±2% (216).

The distribution of solar electromagnetic energy as a function of wavelength is plotted in Fig. 5; Fig. 6 shows more details of the ultraviolet region. The spectrum below 1000 $\overset{\circ}{A}$ is not well established and the curves in this region are subject to considerable uncertainty. Total energy incident per year below certain wavelengths of interest is given in Table 9; this includes both steady radiation and that which may be associated with flares (216, 222). Approximately half the energy of sunlight lies in the infrared and radio frequency regions, 40% in the visible (4000 to 7000 $\overset{\circ}{A}$), and 10% in the ultraviolet and X-ray spectral regions (Table 9). Most of the ultraviolet radiation flux is at 3000 to 4000 $\overset{\circ}{A}$; this radiation, in clear weather, will penetrate the Earth's atmosphere to the surface. About 1% of the total energy is shorter than 3000 $\overset{\circ}{A}$; this short ultraviolet and X-radiation does not pass through the Earth's atmosphere but will be encountered in space. The transition region from atmospheric transmission to absorption is a few hundred angstroms wide.

At the orbit of Venus, the intensity of solar radiation will be 1.9 times that at the Earth's orbit; at the orbit of Mars, about 0.4 times.

Close to the Earth, and in view of the daylight hemisphere, sunlight reflected from the Earth may appreciably increase the total intensity. This reflection is essentially diffuse. The Earth's hemispherical reflectance (albedo) averages 0.36 to 0.39 at visible wavelengths, with seasonal changes from about 0.3 to 0.5 (250, 251). Estimates for the near infrared are about 0.3, for the near ultraviolet about 0.5 (252). The visual albedo of the Moon is approximately 0.06. That of Venus is about 0.65, becoming as high as 0.75 for red light but falling rapidly below 4500 Å to perhaps 0.15 for ultraviolet (229, 250). Mar's albedo at visible wavelengths averages about 0.14, varying from 0.04 at 3000 to 4000 Å to 0.24 at 6400 Å (229, 253, 254).

Besides reflected sunlight, there will also be thermal emission from the planets at far-infrared wavelengths. Close to the Earth, this amounts to about 2×10^5 erg/cm^2-sec, peaking at 120,000 Å (12 microns). Much less than 1% of this radiation is at visible and ultraviolet wavelengths. The same is true of the radiation from the other planets.

B. Effects of Electromagnetic Radiation on Materials (General)

As discussed in the preceding section of this paper, energetic photons can cause radiation damage to materials. The threshold for atomic displacement by photons is above 10^5 ev, corresponding to wavelengths below 10^{-1} Å. The threshold for ionization, 12 to 25 ev, corresponds to 1000 to 500 Å. Photons of longer wavelengths cause electronic excitation when absorbed in a solid; that is, they raise electrons to higher energy states. Sunlight above 3000 Å and the long wavelength emission from planets are not likely to damage engineering materials,

even though they produce excitation. The reason for this is that if a material cannot withstand exposure to these wavelengths, which constitute the sunlight and other radiation encountered at the Earth's surface, the material is not likely to be of engineering interest (with such exceptions as photographic film). Thus, only the portions of solar radiation that do not reach the Earth's surface (those shorter than 3000 Å) are of concern here. Damage through electronic excitation need then be considered for wavelengths between 500 and 3000 Å. (Excitation occurs together with ionization in materials exposed to wavelengths shorter than 500 Å, but need not be separately treated.) During irradiation, both excitation and ionization can cause photoconductivity, photovoltaic effects, and photo-emission.

The penetration depth (range) of electromagnetic radiation in solids varies greatly with its wavelength and from material to material. In the gamma-ray region, at wavelengths below 10^{-1} Å, ranges can be over 10 cm. For wavelengths between 100 and 1000 Å, penetration in solids is very small, 10^{-4} to 10^{-7} cm. Near a wavelength of 3000 Å, the range in some insulators may again be 10 cm or more. These ranges, as previously mentioned, are those distances or shielding weights at which the intensity falls by a factor of e. The absorption coefficient is the reciprocal of the range.

At the longer wavelengths, at least, the amount of radiation entering a solid is decreased by reflection at the surface. This decrease is not more than a factor of 10 at normal incidence and is often only a few percent.

Incident electromagnetic radiation can affect the properties of a material only if it is absorbed in the material; for major changes to occur the radiation

must be strongly absorbed, giving a high dose rate per gram. This strong absorption means that the radiation will probably penetrate the material only to a shallow depth. Accordingly, changes in materials induced by electromagnetic radiation are most likely to occur in surface layers. Damage by electromagnetic radiation in space is thus primarily to spacecraft external surfaces and coatings (the main function of which is usually temperature control) and to other exposed optical surfaces.

C. Effects of Electromagnetic Radiation on Metals and Semiconductors

Metals and alloys are unaffected by ionization and excitation. Displacement can be caused only by wavelengths below 10^{-1} Å, amounting to 10^2 to 10^3 erg/cm^2-yr or 10^9 to 10^{10} photons/cm^2-yr (Table 9). These photons will displace 10^{-16} to 10^{-14} of the atoms within their range. As metals and alloys withstand displacements of 10^{-6} of their atoms or more without detriment to engineering properties (Table 7), these materials will not be damaged by solar photons. Photoelectric emission from metals may occur during irradiation.

Minority carrier effects in semiconductor devices can be permanently changed by displacement of 10^{-12} to 10^{-10} of the atoms. The 10^{-16} to 10^{-14} displacement fraction produced by solar photons is several orders of magnitude smaller, so will cause no permanent changes in engineering properties of semiconductors. Ionization and electron excitation do create electron-hole pairs which change electrical properties of semiconductors during irradiation. The resulting photoconductive and photovoltaic effects are often desired on spacecraft, as in solar cells and radiation detectors. When they are not desired, a few mg/cm^2 of opaque shielding will stop photons down to about 10 Å wavelength.

D. Effects of Electromagnetic Radiation on Inorganic Insulators

Engineering properties of inorganic insulators are affected by atomic displacements only when 10^{-11} or more of the atoms are displaced (Table 7). Sunlight, as mentioned above, produces only 10^{-16} to 10^{-14} fractional displacements per year. Ionization may be more important; sunlight of the wavelengths below 500 to 1000 Å provides 10^8 erg/cm^2-yr of ionizing radiation (Table 9). Ranges at 100 to 1000 Å are not well known but are between 10^{-4} and 10^{-7} g/cm^2. The resulting ionization dose is then 10^{12} to 10^{15} erg/g-yr. This will damage the thin layer reached by the radiation (Table 7). Because the layer is so thin, the effect of most engineering interest is probably the increased optical absorption; some increase in surface electrical conductivity may also occur and could be of concern. Changes in dimensions and mechanical properties may take place also, but because they are confined to such thin surface layers they are not likely to be important. The electronic excitation caused by wavelengths up to 3000 Å also affects optical behavior. The mechanism is as follows: excitation or ionization releases electrons from their equilibrium positions in the crystal lattice; some electrons do not return to these positions but become trapped elsewhere in the lattice, forming "color centers"; the "holes" remaining may also be trapped (255). Color centers absorb light in spectral regions which are different for each material but are usually in the visible or ultraviolet regions. This absorption changes the color of the material and produces a general darkening. Darkening is most likely to matter in transparent optical surfaces and in light-colored pigments used in temperature-control surfaces.

Color centers produced by ultraviolet and X-radiation generally tend to bleach out on exposure to the light which they can absorb. The amount of light (number of photons) absorbed in a color center before its disappearance may be anywhere from 1/10 to 100 times that required to produce the center (255, 256). Thus, color centers produced by the 1% of sunlight below 3000 Å may appreciably affect the absorption of solar radiation at longer wavelengths. Sensitivity to coloration of this sort is not fixed for a given engineering material but may be increased greatly by impurities and lattice imperfections, variations from stoichiometry, strain, and prior deformation. Coloration generally decreases with increasing temperature. Relatively little work has been done on coloration by wavelengths below 3000 Å in the presence of the longer components of sunlight. Because of these uncertainties, it is difficult to reach quantitative conclusions concerning behavior in space environment, even though a great deal of laboratory work has been done on color centers.

Subject to these limitations, it may be said that titanium dioxide, the white pigment commonly used in high quality paints, is especially sensitive to color center development, turning yellow. Commercial titanium dioxide pigment has been claimed to undergo severe yellowing when exposed to radiation at 2000 to 4000 Å equivalent to one month in space (257). Zirconium dioxide is probably somewhat less sensitive, and aluminum oxide still less so (258). Until more data are obtained, spacecraft engineers planning to use white or light colored pigments composed of insulating materials such as oxides will probably have to run their own tests of resistance to ultraviolet radiation on the specific make and grade of pigment with which they are concerned. In dark pigments, intended to

absorb visible and ultraviolet light, exposure to sunlight is not likely to cause any change of engineering significance.

Most glasses, it appears, will undergo color center development and corresponding loss of optical transmission on exposures to sunlight that will be encountered in space (259, 260). These color centers will be partially but probably not completely bleached by exposure to the longer ultraviolet and visible radiation accompanying the short wavelengths that cause discoloration (259, 261, 262). "Non-browning" optical glasses, containing cerium, have been developed for high resistance to discoloration by neutrons and gamma rays. Discoloration by ultraviolet radiation is also reduced by cerium and perhaps by lead (263). High-purity fused silica is available which will absorb, without discoloration, 100 times more nuclear radiation than fused silica of ordinary purity (195); this material is probably also relatively resistant to discoloration by sunlight.

E. Effects of Electromagnetic Radiation on Organic Materials

Organic materials, like inorganic insulators, will receive ionization dosages of 10^{12} to 10^{15} erg/g-yr from sunlight of 100 to 1000 Å wavelength in surface layers 10^{-4} to 10^{-7} cm thick. Such doses will cause severe damage to the properties of thin exposed layers of all known polymers (Table 7). The changes in optical properties--reflectivity, absorptivity, and transmission--are again most likely to be of engineering importance, although increased surface conductivity may also be of importance. Electronic excitation produced by the solar wavelengths 1000 to 3000 Å can also produce significant property changes and to considerably greater depths (264). Even if the 5×10^{11} erg/cm^2-yr contained in sunlight

below 3000 Å is spread over a depth as great as 10 cm (about 10 g/cm^2), the excitation dose would be 5 x 10^{10} erg/g-yr. Ionization doses of this magnitude damage most organics (Table 7); excitation doses may cause somewhat less damage but are still likely to be significant.

Let us, therefore, examine more closely the nature of the changes produced in polymers by ultraviolet light. Excitation in the presence of air produces free radicals which cause two general types of chemical change in high polymers: first, decomposition of polymer chains into smaller fragments, and second, cross-linking of the chains. Decomposition is usually accompanied by loss of mechanical strength and elastic deflection and degradation of electrical properties; it is greatly retarded by the absence of air, as in space vacuum. The second process, cross-linking, is more important in space. Cross-linking, up to a point, increases mechanical hardness and strength and does not degrade the electrical properties of engineering interest. Cross-linking reduces elastic deflection and is, therefore, usually undesirable in elastomers. If continued, it eventually embrittles other polymers to the point where surface flaking and fractures occur. Also, the free radicals mentioned have characteristic optical absorptions.

No direct experiments have been reported on irradiation of polymers with wavelengths of 100 to 1000 Å, and only limited experiments have been reported on irradiation in vacuum at 1000 to 3000 Å. In the later experiments, films of commercial phenyl silicone, vinyl chloride, and methyl methacrylate polymers underwent appreciable cross-linking on exposure equivalent to a few days in space sunlight; at 70°C (160°F), unvulcanized natural rubber underwent appreciable cross-linking

in less than a day (265, 266). At exposures corresponding to a week or two in space, polyethylene, polyethylene terephalate (mylar), polyvinyl chloride (plasticized), and in some tests, polytetrafluoroethylene, were discolored and lost much of their mechanical strength and elongation or flexibility (267, 268). At exposure equivalent to a month to a year in space, a phenyl methyl silicone (at 90°C, 200°F) suffered severe loss of bend flexibility (269). The absorption coefficient has shown moderate increases. Measurements on a polyester, for example, indicate that after the first few hours in which little change occurred, 2000 to 3000 Å radiation 5 times more intense than in space increased the absorption coefficient at 4300 Å about 2 cm^{-1} for each factor of 10 increase in time of exposure (270). A relation of the form mentioned implies, by the way, that most of the darkening would occur in the first few weeks of exposure to sunlight.

In general, irradiation in vacuum to simulated sunlight at 1000 to 3000 Å had less effect on polymer mechanical and electrical properties than did exposure in air to the much higher flux above 3000 Å contained in the sunlight that reaches the Earth's surface (265, 266, 271). This may not be true of optical properties.

The exposure at which a given damage was reached was increased 3 to 10 times by addition of suitable stabilizers. This improvement is much less than under Earth conditions, where the radiation is above 3000 Å. The choice of stabilizer for space exposure is restricted by its evaporation in vacuum at temperatures of service (270, 271). (In air, at least, some additions act as sensitizers and accelerate changes during irradiation by ultraviolet light (264).) In paint films, addition of pigments considerably retarded damage by radiation longer than 2000 Å (269). As previously mentioned, however, pigments themselves may suffer color

changes under irradiation, even at doses too low to affect polymers (Table 7). In nonoptical applications, a polymer can often be protected from sunlight by an opaque coating; an evaporated aluminum coating on a polyethylene terephthalate film is an example (268).

It should be re-emphasized that the experiments mentioned in the preceding three paragraphs did not include exposure to radiation at 100 to 1000 Å; the intense but very shallow surface damage resulting from such exposure was not reproduced.

F. Laboratory Simulation of Space Sunlight Exposure

It is a considerable undertaking to reproduce experimentally in the laboratory the solar spectrum below 3000 Å. For materials evaluation it would be convenient to be able to simulate the effects of solar electromagnetic radiation with a source of different spectral distribution and intensity. Some authors have indicated that, for polymers, the ultraviolet wavelengths used are not specific in the 1000 to 2900 Å region, and that the total incident energy flux in this region is the important quantity (269). More pertinent than the incident flux, however, should be the energy absorbed in a given volume or mass (270, 272). Since the absorption may vary strongly with wavelength, the intensity of radiation in the laboratory may have to be adjusted to fit the polymer if the spectrum of this radiation differs from that of space sunlight.

In particular, the effects of solar photons shorter than 1000 Å should be reproduced. This is not easy to do on Earth; among other difficulties, all solids are "opaque" at 100 to 1000 Å wavelengths and will not serve as "windows" for

experimental equipment operating in this region. One laboratory approach would be to put the specimens essentially inside an X-ray or discharge tube operating at a few hundred volts. An alternative would be to use electron irradiation to produce ionization matching that of the solar photons.

For experiments on inorganic insulators, too, the importance of the photon wavelength distribution is not well established. The 100 to 1000 Å wavelength region should certainly be considered. If effects of irradiation on optical absorption are to be determined, the experimental exposure should be at a wavelength shorter than that at which the absorption is measured, and should provide at least as many photons as will be encountered below this wavelength in sunlight.

Even when the percentage distribution of energy in the solar spectrum is adequately simulated, increasing the intensity by, say, a factor of 10 is not necessarily equivalent to increasing the exposure time by the same amount; it may be equivalent to increasing the exposure time by $\sqrt{10}$ or even less. In other words, the reciprocity law does not hold. The applicable relation depends on the exact material used and on the exposure conditions (271). Therefore, accelerated tests are not easy to interpret quantitatively unless the effect of intensity is determined in each case.

VI. EFFECTS OF METEOROIDS

A. Meteoric Particles in Space

It has been long recognized that meteoric particles can damage space vehicles. These particles, collectively called "meteoroids," may be divided into three classes: meteorites, meteors, and micrometeorites or dust. These classes differ in mass, density, orbit, and origin.

Meteorites are objects from space which occasionally fall to Earth. They are primarily stony fragments, having densities of 3 to 3.5 gm/cm^3; about 10% are iron-nickel fragments with densities of 7 to 8 gm/cm^3. Meteorites are believed to be of asteroidal origin. Their masses are often above 1 gm; the flux above a given mass, near the Earth, is shown in Fig. 7. Their orbits around the Sun are, for the most part, circular, not far from the ecliptic (the plane of the Earth's orbit), and their direction of revolution is direct (the same as the Earth's). Their velocities relative to the Earth, or to a spacecraft traveling around, to or from the Earth, are usually about 20 km/sec, though an occasional meteorite may have a relative velocity as high as 72 km/sec, the maximum velocity for head-on collision with the Earth of a body in orbit around the Sun. Meteorites do not concentrate around the Earth, but the concentration probably increases considerably toward the asteroidal belt, between the orbits of Mars and Jupiter. Near the Earth's orbit, at least, the flux is so low that the chance of a meteorite colliding with a spacecraft is negligible (287-289).

Meteors are flashes in the Earth's atmosphere caused by the entrance of meteoric particles, and are detected by eye, by photography, or by radio or radar. The

overwhelming majority of the particles which cause meteors are not meteorites, but come from a different population. They are believed to be fragments of comets from which volatile materials have been lost. No special name has been given these particles, which are far more numerous than meteorites. They are mostly porous "dustballs," with a very low over-all density, probably near 0.1 gm/cm^3. The mass is generally less than 1 gm; the limit of detectability is approximately 10^{-5} gm. Data on flux above a given mass are shown in Fig. 7. These data are subject to an uncertainty of an order of magnitude in the scale of masses; also there are variations of about a factor of 3 from one portion of the Earth's orbit to another. The orbits are elliptical, mostly with high eccentricities, and occur at all angles to the plane of the ecliptic. The direction of revolution of some of these meteoroids is retrograde (opposite to the Earth's); the majority, however, are in direct, low-inclination orbits. Meteoric particles of the sizes visible on hitting the atmosphere do not concentrate around the Earth. Their velocities relative to the Earth, an Earth satellite, or a spacecraft travelling to or from the Earth range from a few km/sec outside the Earth's gravitation field up to about 72 km/sec, and average about 30 km/sec. Close to the Earth, the minimum velocity is increased by the Earth's gravitational field to 11 km/sec. Closer to the Sun, velocities increase (282-284, 290-295).

Some of the meteors are associated in "showers." The particles responsible for them move together in elliptic orbits, which the Earth may intersect once or twice a year. In some cases these meteoroids are almost uniformly distributed along the orbit; in others they are concentrated at one point in the orbit so that high fluxes are encountered at the Earth only once in many years. Fluxes may

range up to 10^5 times normal sporadic background, but are commonly 10^1 times background. For the Earth or a spacecraft crossing their orbit, these high fluxes last from a few hours to a few days. The mass distribution in a shower is generally different from that for sporadics. While some showers seem to consist of particles near 10^0 gm or larger, others probably consist mostly of smaller particles (282, 290, 292-293, 296-298).

Interplanetary space also contains a considerable amount of fine dust or micrometeorites. It is generally believed that this dust belongs to the same population as the particles which cause visible meteors, and is of the same cometary origin. The small dust particles may be denser, however, because they may be the stony particles which in porous clumps form larger meteoroids; alternatively they may be porous aggregates of still smaller particles. The density of the dust particles has not been measured, but estimates range from 0.05 g/cm^3 ("dust-balls") to 3.5 g/cm^3 (stone) for the smaller particles; for larger particles the density is probably closer to 0.05 g/cm^3. Masses, at least for heliocentric orbits, range upward from a lower limit set by solar radiation pressure; this is about 4 x 10^{-10} g at a density of 0.05 g/cm^3 and about 7 x 10^{-14} g at a density of 3.5 g/cm^3. At the upper end, masses of dust particles approach the masses of those which cause radio meteors. Dust orbits around the Sun are mostly near circular and are near the plane of the ecliptic. It is not known what percentage are in direct orbits and what percentage in retrograde, but it is likely that most are in direct orbits. For direct orbits of this sort, the velocities relative to the Earth or to a typical spacecraft are mostly under 20 km/sec; for retrograde orbits the velocity approaches 60 km/sec. Heliocentric orbits of the finer

particles are brought from their originally elliptic shape to almost circular by drag arising from solar radiation pressure (Poynting-Robertson effect) and from electrostatic interactions. These drags also make them spiral slowly inward to the Sun.

The existence of dust in the solar system was first deduced from studies of the "F corona" of the Sun (that is, the sunlight scattered toward the Earth by the dust); these studies provide measurements of the amount of dust. Measurements of dust flux have also been made more recently by sounding rockets, satellites, and space probes. Flux data from both coronal and in-space measurements are given in Fig. 7, in which a wide discrepancy is shown, especially at small sizes, between the corona data, on dust far from the Earth (286), and the rocket and satellite data, mostly on dust near the Earth (273 - 280, 283, 285). Predictions on theoretical grounds of increased dust concentration around the Earth (286, 299) are confirmed by recent examination of the altitude dependence of micrometeoroid flux as measured by sounding rockets, satellites, and space probes (154, 276, 300). Various quantitative relations for this dependence have been suggested; from minimum satellite altitudes outward it seems likely that the flux varies as some power between R_g^{-1} and R_g^{-2}, where R_g is the geocentric radius. The dust cloud around the Earth extends out about 10^6 km. The particles composing it are either spiralling in toward the Earth or orbiting around it; most of those close to the Earth are moving almost tangentially. Velocities relative to Earth probably average 7-15 km/sec at low altitudes, and 3-10 km/sec at higher altitudes. The dust cloud is held by gravitation; atmospheric drag, including electrostatic drag, and interactions with solar radiation pressure may play a

part in the Earth's capture of this dust from heliocentric orbits (154, 286, 299-302).

In interplanetary space the dust concentration increases toward the Sun as about the -3/2 power of solar distance (286). Out of the plane of the Earth's orbit, the concentration is believed to fall by a factor of 2 within 15 deg, with little dust more than 20 deg out of the ecliptic (303). It is not certain whether showers of dust particles accompany the visible showers of large particles; one recent report indicates that they do (304). There is also some evidence of brief bursts of dust, as well as day-to-day fluctuations of a factor of ten or more (275-278, 280).

The fluxes of meteoric particles selected for damage estimates in this paper are shown in Fig. 7. Near the Earth, at low satellite altitude, the flux chosen is

$$\log \Phi = -12.7 - 1.18 \log m \tag{10}$$

where Φ is the flux per meter^2-sec of particles above mass m in grams. This relation lies between two other recently suggested lines (154, 281), as shown in the figure, and uses newer data on the mass scale of meteors (305). Away from the Earth, but at about the Earth's distance from the Sun and in the ecliptic plane, the selected relation is

$$\log \Phi = -12.4 - 0.69 \log m \tag{11}$$

To calculate effects of meteoroids on materials, their velocity will be taken as 15 km/sec geocentric up to log m = -6.6 and 28 km/sec above

log m = -1.4, with an interpolation approximately linear for intermediate masses (291). In addition, a fast component at 60 km/sec, arising from meteoroids in retrograde solar orbits, is assumed to constitute 10% of the flux close to Earth above log m = -1.4, falling to 0% at log m = -6.6 (292-294). Away from the Earth, this fast component is assumed to constitute 40% of the geocentric flux (14% of the heliocentric) below log m = -6.6 and 10% above log m = -1.4.

Both Fig. 7 and the discussion above show that there are considerable uncertainties in the flux, velocity, density, and distribution of meteoric particles.

B. Meteoric Erosion and Perforation

The effect of a meteoroid upon a material which it strikes is at present best determined theoretically, because it has proven very difficult to accelerate particles of known mass to the velocity range of primary interest. Extrapolations from effects at lower velocities are not trustworthy because, at meteoric velocities, both the particle and the plate which it strikes behave hydrodynamically, whereas at lower, experimental, velocities the particle tends to retain its shape during the impact (306). The most important theoretical work is that of Bjork, who considered an aluminum projectile hitting a thick (semi-infinite) aluminum plate at meteoric velocities and an iron projectile hitting a thick iron plate (281, 307). The approach is a numerical solution on a digital computer of the hydrodynamic equations for behavior of the materials, utilizing experimental data on their compressibility (equations of state). The strength of the metals is taken as negligible in comparison with the high pressures involved; heat transfer and viscous effects are also neglected. Melting and vaporization do not play an

important part in penetration. Even if they occur, they will have little effect on the process, which is considered hydrodynamic in any case. Bjork finds that the penetration depth of an aluminum particle hitting an aluminum plate at meteoric velocities is

$$q = 1.09 \, (mv)^{1/3} \qquad (12)$$

and for iron hitting iron is

$$q = 0.606 \, (mv)^{1/3} \qquad (13)$$

Here q is the depth and radius in cm of the hemispherical crater formed; m is the projectile mass in g; ar : v is the impact velocity in km/sec. As a partial confirmation, experimental data for a lead projectile against a lead plate (308-312) may be used; the velocity needed to achieve hydrodynamic behavior (hyper-velocity impact) for lead is only about 3 km/sec, whereas for structural metals about 7 to 8 km/sec is needed (312, 313). The lead data are consistent with

$$q = 1.3 \, (mv)^{1/3} \qquad (14)$$

There has been no adequate analysis of the effect of projectile composition or density on penetration depth; one measurement for aluminum on steel shows a penetration depth 16% less than Eq (13) gives for iron on iron (314). This suggests only a slight dependence on meteoroid density ρ_m, here about $\rho_m^{-0.18}$. On this basis most of the difference between the aluminum-on-aluminum and iron-on-iron results would be attributed to differences in target density ρ_t; Eq (12) and (13) indicate that the crater depth varies as about $\rho_t^{-1/2}$. The

- 55 -

lead data do not fit this relation, suggesting that compressibility differences should also be considered, but the compressibility of meteoric dustballs is not known.

The above equations are for impact at normal incidence (90 deg). Experiments indicate that for oblique incidence the crater remains approximately hemispherical, and its depth depends on the normal component of the velocity vector (315).

The volume of material removed from the target plate by the impact has not been calculated and would depend to some extent on the strength and toughness of the material. The volume removed is, however, related to the crater volume by a factor of the order of magnitude of unity. In the absence of information, this will be taken as unity. Equations (12) and (13) may then be combined with the meteoroid flux and velocity values given earlier to provide estimates of erosion by meteoroids and of the frequency of perforation by meteoroids.

One then finds that away from the Earth the total volume lost by meteoric erosion is less than 1 $\overset{\circ}{A}$/yr; close to the Earth, at low satellite altitude, it is about 200 $\overset{\circ}{A}$/yr. This erosion will be in the form of small hemispherical pits. The pit diameter will generally be less than 10^{-3} cm if the dust has the density of solid stone and 10^{-2} cm if it is very porous. The number of pits will run, for solid stone particles, 1 per few cm^2-yr away from Earth and over 10^4 per cm^2-yr at low altitude. For porous dust, the number is about 10^{-3} cm^{-2}-yr^{-1} away from Earth and 10^1 cm^{-2}-yr^{-1} at low altitude. In brittle materials, such as glass and plastics, each pit will be surrounded by an area of cracks, or very shallow spall, several times the pit diameter (306).

A check of the above estimates can be obtained from examination of meteorites, picked up on Earth, whose ages have been measured by isotope analysis (153-156). Erosion of these pieces by smaller meteoroids and by other sources while they were far from Earth was less than 30 Å/yr and probably less than 1 Å/yr, as previously mentioned; this is in agreement with the preceeding paragraph. The amount of dust erosion expected is thus so small that the effect, if any, on engineering properties will probably be limited to degradation of optical properties of exposed lenses, mirrors, and windows.

The average frequency of perforations by meteoroids near the Earth and away from the Earth is given in Fig. 8. These curves were obtained from the fluxes of Fig. 7 and the crater sizes of Eq (12) and (13) on the assumption that at a given meteoroid momentum the thickness of plate perforated will be 1.5 times the depth of the crater in a semi-infinite plate. Uncertainties in the mass scale of meteors and in the effect of particle density upon crater size combine in such a way as to introduce uncertainty of a factor of 3 in the thickness perforated; the values chosen are conservative. For spacecraft materials lighter than aluminum and iron (steel), it is probably conservative to assume that the thickness perforated will vary as the square root of the density; low density materials will thus suffer fewer perforations per unit weight. The strength of the material has little effect.

C. Spaced Armor

There has been considerable interest in the possibility of using "meteoroid bumpers," additional plates spaced out in front of the main skin, to reduce

meteoroid perforation. Such arrangements, under the name of "spaced armor," have been familiar for many years to those working on the military shot-versus-armor problem. The function of the bumper is simply to break the meteoroid into smaller pieces which will disperse and so spread the impact over a larger area of the main target plate, enabling it to stop them more easily. For this purpose, the bumper should be as thin as possible and still break up the meteoroid; this permits using a maximum percentage of the allowable weight in the main plate, which stops the fragments. Experiment (316) and theory (317) show that even an aluminum projectile shatters on striking an aluminum plate 1/10 its own thickness at 6-20 km/sec. A glass projectile was shattered by striking an ethylene terephthalate (mylar) film 0.4% of its own thickness at as low as 2 km/sec (318). Since the larger particles of cosmic dust are believed to be porous dust-balls very weakly held together, they can be shattered by extremely thin bumpers; thus, the bumper thickness can be the minimum permitted by fabrication procedures.

If the shattered fragments are so spread out that they act independently on hitting the main plate, the momentum and energy transmitted to the plate at each point of impact are reduced in proportion to the number of fragments. As the penetration depth varies as the 1/3 power of the momentum (Eq. 12-14), shattering the meteoroid into two fragments would permit reducing the main plate thickness to 80% of original value, 10 fragments to 46%, 100 fragments to 22%, and 1000 fragments to 10%. Experiments indicate that about 33% is an average value, provided the spacing between bumper and main plate is adequate (319-321). This spacing is necessary for the shattered fragments to spread out behind

the bumper and so increase the area of main plate which absorbs the impact. An elastic analysis (possibly an oversimplification) shows that the distance of spread at a given spacing is inversely proportional to the square root of bumper weight per unit area. The proportionality constant has been determined by comparison with limited experimental data (320-322) and with hydrodynamic calculations (317) of the angle of fragment spread for an aluminum projectile passing through a thin aluminum plate. (For the latter it was assumed that the fragments should be spread over a radius twice that of a crater in an unbumpered plate.) The proportionality constant involves the meteoroid density. If the main plate thickness is taken as 1/2 the crater depth given by Eq. (12) and (13) (3/2 the crater depth to allow for finite thickness, times 1/3 because of presence of the bumper), then for low density dustballs the spacing s between main plate and bumper should be about

$$s = 2t_t \sqrt{t_t/t_b \rho_b} \tag{15}$$

where

t_t = thickness of main target plate

t_b = thickness of bumper

ρ_b = density of bumper, in gm/cm^3

This indicates, for example, that an aluminum bumper 1% of the thickness of the main plate should be spaced out 12 times the main plate thickness. Greater spacing is of little help; smaller spacing will increase the required main plate thickness from 1/3 to 1 times the unbumpered value in about a linear relationship (320).

It may be noted that little or no advantage is to be expected from using more complex arrays, with many plates, or from using closely spaced plates; performance may even be reduced by such arrangements. Foam or other low density materials may be useful, however, as a convenient means to maintain wide spacings.

D. Spalling by Meteoroids

When a meteoroid hits a plate, it not only makes a hemispherical crater on the front surface, but also initiates a strong compressive shock which travels through the plate thickness and is generally reflected off the inner surface of the plate as a tensile stress. This stress is likely to cause a piece of the inside surface of the plate to be ejected inward at high velocity, which may cause serious damage to components or personnel inside the spacecraft. This phenomenon, called "spalling," is common in ordinary armor penetration by shot and shell. The diameter of the piece spalled off the inside is usually several times the plate thickness; the spall thickness may be from about 1/10 to 1/2 the plate thickness. If the part hit contains fuel or coolant, fragments may be carried by the fluid into critical parts.

Limited analytical data are available from which to develop an expression for the height of the compression pulse. The stress σ at the peak of the pulse in a given semi-infinite material would be expected to depend upon the meteoroid velocity v, density ρ_m, and radius r, and on the distance D from the point of impact, in some fashion such as

$$\sigma = Z \rho_m^y v^x \left(\frac{D}{r}\right)^w \tag{16}$$

where w, x, y, and Z are constants. One would also expect the effect of the meteoroid to appear through a product such as its momentum, $\rho_m r^3 v$, or its energy, $\rho_m r^3 v^2$. Equation (16) would then be

$$\sigma = Z(\rho_m r^3 v^n)^y D^w \tag{17}$$

Comparing Eq (16) and (17),

$$3y = -w \tag{18}$$

and

$$ny = x \tag{19}$$

or

$$n = \frac{x}{y} = \frac{x}{-w/3} = \frac{-3x}{w} \tag{20}$$

Available numerical calculations (317) on iron and aluminum at distances D large compared to the particle radius r and at moderate to high stress levels indicate that $x \simeq 1.67$, and $w \simeq -2.65$, so $n \simeq 1.9$. This strongly suggests a velocity exponent of 2 (energy) rather than 1 (momentum) in the product which characterizes the meteoroid. On this basis, the available data (317) lead to the relation

$$D = 5.2 E^{1/3} \sigma^{-0.378} \tag{21}$$

where D is in cm, E is the meteoroid kinetic energy in ergs, and σ is the stress within the target in megabars. The difference in D between aluminum and iron targets is only about 8% and has here been neglected.

This equation may be used to calculate the thickness of target plate necessary to reduce the level of the reflected tensile stress to within the strength of

the plate material. For tough, sound metals, experimental studies of spalling induced by explosives indicate that the fracture strength, under the conditions of stress distribution and rate of loading involved, is roughly three times the tensile strength in an ordinary tensile test (323). Inserting these values for σ, one obtains for a tough aluminum alloy at 70, 000 lb/in.^{2} tensile strength,

$$D = E^{1/3}/1300 \text{ cm} = E^{1/3}/3300 \text{ in.} \tag{22}$$

and for a tough steel at 220, 000 lb/in.^{2}, tensile strength,

$$D = E^{1/3}/2000 \text{ cm} = E^{1/3}/5100 \text{ in.} \tag{23}$$

Combining these equations with the meteoroid data of Fig. 7, the spalling curves of Fig. 9 are obtained. It will be seen that spalling will occur at thicknesses twice to three times those adequate to prevent perforation.

The assumed fracture stress value of three times the static tensile strength applies only to tough materials. Many high-strength metals and alloys, including many steels and aluminum alloys, are brittle under high rate of loading. Many metallic and non-metallic plate and sheet materials have strongly directional properties with very low tensile strengths through the thickness direction; many delaminate readily and will accordingly spall even in very heavy thicknesses, as the fracture stress to be inserted in Eq. (21) will be very low.

It is possible to reduce somewhat the tendency to spall by building the spacecraft skin of layers of properly selected material (324, 325). The pertinent material property is the acoustic resistance $G = \rho_t c$, where ρ_t is the density of the target plate and c the velocity of shock wave propagation in the plate under

the stress conditions encountered. If a compressive stress pulse σ_I in a material with acoustic resistance G_1 reaches an interface between this material and one with acoustic resistance G_2, the pulse σ_R reflected from the interface will have the height

$$\sigma_R = \frac{G_2 - G_1}{G_2 + G_1} \sigma_I \qquad (24)$$

and there will be a pulse σ_T transmitted through the second material with height

$$\sigma_T = \frac{2G_2}{G_2 + G_1} \sigma_I \qquad (25)$$

If $G_2 < G_1$, the compression σ_T transmitted into the second material will be less than the incident compression pulse σ_I, and the tension reflected into the first material will also be less than σ_I. The stress pulse may thus be divided up and attenuated to a greater extent than in an equal weight of homogeneous material (325). It is necessary, however, that the joint efficiency be near unity to avoid spalling at the joint.

Another possible approach is to cover the front surface of the plate with finely divided particles of appropriate shapes (325). The idea here is to attenuate the pulse by reflecting it repeatedly at the particle boundaries. The particle layer would have to be thick enough so that much of the front-surface crater would occur in these particles and not in the underlying plate.

This approach leads to consideration of the effect of a bumper upon spalling. The thickness required to avoid spalling varies, approximately, as the 1/3 power of the impact energy (Eq. 22 and 23), or the -1/3 power of the number

of fragments into which a meteorite is broken by the bumper. This is the same dependence as that for perforation, outlined above. Accordingly, the permissible percentage reduction in main plate thickness when a bumper is used is the same whether the thickness is governed by perforation or by spalling considerations. A rough calculation indicates that spacings of bumper and main plate which give fragment spread adequate to decrease perforation should also separate the pulse waves which the fragments generate in the main plate sufficiently to avoid serious pulse overlap at the rear surface.

E. Other Effects of Meteoroids

Besides producing erosion, perforation, and spalling, meteoroid impacts set up pressure pulses in a space vehicle structure which may damage equipment even if no spalling occurs. In particular, when a meteoroid hits a container holding liquid, the pressure pulse transmitted to and through the liquid may break the container.

VII. DESIGN APPROACHES AND SPACE EXPERIENCE

It may be of value to consider design approaches which should minimize difficulties arising from the effects of space environments on materials, together with some of the experience obtained from space flights already carried out.

To avoid difficulties with sublimation and decomposition, choice of suitable material seems the best approach. For inorganics, good data are generally available; for polymers, it would be wise either to be conservative, choosing materials known to be safe, or to run tests on doubtful materials. Polymers

suitable for high-temperature service are generally best; the use of plasticizers should be avoided. Epoxy-glass laminates, together with magnesium, were extensively used in Pioneers 3 and 4 and gave no trouble over the battery lifetime of a few days. In Explorers 1, 3, and 4, which transmitted for several months, phenolic-cloth insulating bulkheads were employed successfully. The secondary structure of Explorer 7 was a polyester-glass laminate; the temperature control surfaces were silicone paint; both performed properly for well over a year. The Echo balloon consisted of aluminized ethylene terephthalate 0.0013 cm (0.0005 in.) thick; it too has operated for over a year (326). It may be noted that though a nonvolatile stable coating or surface finish applied over a more volatile or less stable material may be useful, the coating would usually need to be nonporous.

For lubrication, several techniques may be employed separately or, preferably, in combination. Although not an ideal solution, seals seem to be the method of first choice; hermetic seals, where usable, should be more reliable than dynamic; the leakage rate for the latter is less reproducible. Low vapor pressure greases or possibly oils of known good vacuum performance can often be used; methods of lubricant resupply to insure continued lubrication could be incorporated for extended missions. A diester oil was used satisfactorily as lubricant for the shielded ball bearings in the tape recorder of Explorer 3. In Tiros 2, radiometer ball bearings using a similar oil have again operated for several months; sintered nylon sleeves impregnated with the oil provided a lubricant reservoir, and close shaft clearances minimized the opening through which oil vapor could escape (327). Solid lubricants--molybdenum disulfide, silver or

gold films, and tetrafluoroethylene--also should be of value in appropriate applications and can be applied in many ways.

Effects of solar electromagnetic radiation are probably important only for optical elements and light-colored temperature control surfaces, and then only on the outer surface of the space vehicle. For optical elements, use of radiation-resistant ("nonbrowning") glass and, where possible, of high-purity fused silica appears advisable. Heating in flight may sometimes be useful as a means of bleaching any discoloration. Light-colored pigments which are resistant to development of color centers and in which color centers bleach out readily in visible and infrared light should be selected for temperature control surfaces. Organic paint vehicles, if used on external temperature control surfaces, should be chosen from among those polymers high in radiation-resistance. The successful use of silicone paint on Explorer 7 and of aluminized ethylene terephthalate on Echo has been mentioned. Explorers 1, 3 and 4 had temperature control surfaces of sprayed aluminum oxide and lightly oxidized stainless steel which performed well.

If charged particles are likely to cause damage, it is desirable to use the more radiation-resistant materials within a class, and where possible the most resistant classes, such as metals, should be selected. Polymers were nevertheless employed with no apparent malfunctions, in the inner Van Allen belt, with minimal shielding on Echo and with little more shielding on Explorer 1, 3 and 4. For some regions of space and some types of material even a little shielding may give protection; sensitive materials should not be placed on the extreme outer skin when this can be avoided. The glass covers of solar cells

are believed to have been darkened in a month or two by radiation in the outer Van Allen zone on Explorer 6 and by solar flare particles on Pioneer 5; this pro-probably was the cause of observed increases in temperature (328). The silicon solar cells of these spacecraft also suffered radiation damage (118).

Because radiation damage in inorganic materials is reduced by heating, an increase in operating temperature, when permissible, may be of value. Thus on Vanguard 1, in the inner radiation belt, a combination of high operating temperature and low demand apparently has prevented damage sufficient to affect operation (118). The directionality of charged particle motion in space may be used to advantage in placing sensitive elements in positions aboard the vehicle where the charged particle flux will be minimized.

Little can be done to prevent meteoroid damage to optical surfaces. For other surfaces, properly designed spaced shields offer appreciable weight savings over a single solid shield in reducing perforation and spalling. Some advantage may be taken of meteoroid directionality. For vessels holding fluid, compartmentation may be helpful. It may also be possible to develop self-sealing methods for vessels operating near room temperature. On Echo, at altitudes as low as 1000 km (600 miles), the relatively low rate of gas loss which has occurred suggests a corresponding low rate of meteoroid puncture of the thin plastic balloon (329). On the other hand, failure of both transmitters on Explorer 3 coincided with a high measured rate of meteoroid hits during a shower and it has been suggested that damage by meteoroids caused the failures (330).

In designing materials to withstand space environment, the duration and position in space of the exposure must be considered. A material that would be

completely destroyed by exposure for a year or two may be perfectly satisfactory for a few hours or days. Likewise, a material that would break down in the Earth's radiation belts may be satisfactory below or above them; a wall that would be quickly pierced or spalled by meteoroids in a low satellite orbit may be quite satisfactory if used far from Earth. Perhaps the most elementary example is that a material unsatisfactory in sunlight may work quite well in the Earth's shadow.

VIII. SUMMARY

It may be useful to summarize the effects of space environments on each class of material.

Metals and alloys are generally quite stable in the high vacuum of space at normal operating temperatures. Sublimation of cadmium and zinc may be of some concern, particularly where there is a possibility of the metal plating out in an uncontrolled manner on a cold insulating surface. Sublimation of magnesium and its alloys becomes appreciable above 175°C (350°F). A slight roughening of polished optical surfaces of other metals may occur through selective sublimation. Frictional behavior of contacting metal surfaces in space environment is a problem, with uncertainties resulting from the lack of reliable data on friction in ultrahigh vacuum. The small amount of data available indicates that similar metals will usually seize when in sliding contact in high vacuum. There is a smaller probability that dissimilar metals or alloys will seize.

Metals and alloys are not affected by space sunlight. Particle radiation will also have no effect, except that in shallow surface layers there may be a change in ferromagnetic properties on exposure to the Earth's inner radiation belt or to low-energy solar protons.

Meteoroids will occasionally perforate metal walls; spalling of fragments off inner surfaces by meteoroid impact on metallic spacecraft structures will be more frequent. These problems are greatest closest to the Earth and diminish with increasing distances from the Earth. Micrometeoroids can produce a sand-blasting effect on polished metallic optical surfaces on low-altitude satellites.

Among the semiconductors, selenium, phosphides, and arsenides have high sublimation or decomposition rates in high vacuum at moderate temperatures. Semiconductor devices undergo no permanent damage from sunlight. The Earth's inner radiation belt will seriously damage semiconductor properties; in the outer belt, only the more sensitive devices will be permanently affected and then only if the sensitive portion is close to an exposed surface. Solar particle emissions may damage exposed surfaces of all semiconductors and will possibly affect sensitive semiconductors even through appreciable shielding. Meteoroids may cause shorting in exposed semiconductor surfaces.

Most inorganic engineering insulators are unaffected by the vacuum of space except at high temperatures. Sunlight in space affects primarily optical properties of insulators, causing darkening. Such pigments as titania and zircon are probably poor in this respect, as are most glasses. Glasses containing ceria may be better; high purity silica certainly is. Glasses will suffer radiation damage to their optical properties in both of the radiation belts and possibly when

subjected to solar particle emissions. Electrical and mechanical properties close to the exposed surface of inorganic insulators may be affected by both radiation belts. Close to the Earth, optical surfaces will undergo appreciable surface damage by meteoroid dust.

Because of the complex composition of most oil and grease lubricants, simple estimates of their evaporation rates may not be reliable. Even oils and greases that do not evaporate in vacuum may not lubricate satisfactorily under vacuum; thus, lubrication tests in vacuum are needed. Some petroleum-base, some diester, and some silicone oils and greases are satisfactory, but others are not. Oils and greases are unaffected by radiation in space, except in the Van Allen belts. Fatty acids and graphite are of no value for lubrication in space environment, and diamond is a poor vacuum bearing material. Molybdenum disulfide, however, will apparently lubricate in vacuum.

Such polymers as nylon, acrylics, polysulfides, and neoprene show high decomposition rates in vacuum. On the other hand, some commonly used elastomers--vinylidene fluoride-hexafluoropropane, chlorotrifluoroethylene, butadiene-styrene, isoprene and natural rubber--are rather stable in high vacuum. Similarly, such plastics as silicone resins, tetrafluoroethylene, polyethylene, polypropylene, and ethylene terephthalate exhibit good to excellent behavior in high vacuum. Tetrafluoroethylene has excellent lubrication characteristics in high vacuum, but most other polymeric materials are of doubtful value as lubricants in the environment of space.

Optical transmission of polymers will probably be seriously damaged by unfiltered sunlight; the effects on optical absorption and emission are less certain.

Electrical and mechanical properties of polymers will probably be unaffected by sunlight, except in a thin outer layer. In general, exposed polymer surfaces will deteriorate rapidly in the Earth's radiation belts and perhaps from solar particle emissions. The flexibility, strength and electrical characteristics of tetrafluoroethylene, nylon, acrylics, polysulfides, butyl rubber and similar materials will be detrimentally affected in the radiation belts even through heavy shielding. On the other hand, such polymers as styrene, epoxies, filled resins (glass or asbestos reinforced plastics), natural rubber, polyurethane and butadiene-styrene will probably not be affected beneath the surface. Polymers will suffer occasional perforation by meteoroids; structural laminates will probably also undergo severe spalling of their inner surfaces when struck. Near Earth, roughening by meteoric dust will affect exposed optical surfaces of polymeric materials.

There are many hazards of space whose importance to materials has been over-emphasized in the past. Among the occurences unlikely to be of engineering importance are sublimation of aluminum alloys and steels, vacuum decomposition of tetrafluoroethylene, polyethylene, and most rubbers, escape of gases through solid container walls, sputtering of atoms off a surface by collision with atoms or ions in space, meteoric erosion away from the Earth, and radiation damage by cosmic rays.

This summary is intended to highlight and generalize the behavior of materials in space environments. The details are covered in the text, in which the environment of each portion of space is discussed with particular reference to its effect upon particular materials.

ACKNOWLEDGMENTS

Table 1. Gas pressures in space

Altitude	Pressure, mm Hg	Temperature		Concentration molecules, atoms, or ions/cm³	Composition
		°C	°F		
Sea level	$760 \cong 10^3$	-40 to +40	-40 to +105	2.5×10^{19}	78% N_2, 21% O_2, 1% A
30 km (100,000 ft)	$90 \cong 10^2$	-40	-40	4×10^{17}	N_2, O_2, A
200 km (125 mile)	10^{-6}	10^3	10^3	10^{10}	N_2, O, O_2, O^+
800 km (500 mile)	10^{-9}	10^3	10^3	10^6	O, O^+, H
6500 km (4000 mile)	10^{-13}	10^3	10^3	10^3	H^+, H
Above 22,000 km (14,000 mile)	$< 10^{-12}$	10^3 to 10^5	10^3 to 10^5	10^1 to 10^2	85% H^+, 15% He^{++}

Based on References 1-18.

Table 2. Sublimation of metals and semiconductors in high vacuum

Element	Temperature at which sublimation rate is						Melting Point	
	10^{-5} cm/yr (1000 A/yr)		10^{-3} cm/yr (0.0004 in./yr)		10^{-1} cm/yr (0.040 in./yr)			
	°C	°F	°C	°F	°C	°F	°C	°F
Cd	40	100	80	170	120	250	320	610
Se	50	120	80	180	120	240	220	420
Zn	70	160	130	260	180	350	420	790
Mg	110	230	170	340	240	470	650	1200
Te	130	260	180	350	220	430	450	840
Li	150	300	210	410	280	530	180	350
Sb	210	410	270	520	300	570	630	1170
Bi	240	470	320	600	400	750	‹.	520
Pb	270	510	320	630	430	800	330	620
In	400	760	500	940	610	1130	160	310
Mn	450	840	540	1010	650	1200	1240	2270
Ag	480	890	590	1090	700	1300	960	1760
Sn	550	1020	660	1220	800	1480	230	450
Al	550	1020	680	1260	810	1490	660	1220
Be	620	1140	700	1300	840	1540	1280	2330
Cu	630	1160	760	1400	900	1650	1080	1980
Au	660	1220	800	1480	950	1750	1060	1940
Ge	660	1220	800	1480	950	1750	940	1720
Cr	750	1380	870	1600	1000	1840	1880	3410
Fe	770	1420	900	1650	1050	1920	1540	2800
Si	790	1450	920	1690	1080	1970	1410	2570
Ni	800	1460	940	1720	1090	2000	1450	2650
Pd	810	1490	940	1720	1100	2020	1550	2830
Co	820	1500	960	1760	1100	2020	1500	2720
Ti	920	1690	1070	1980	1250	2280	1670	3040
V	1020	1870	1180	2150	1350	2450	1900	3450
Rh	1140	2080	1330	2420	1540	3800	1970	3570
Pt	1160	2120	1340	2440	1560	2840	1770	3220
B	1230	2240	1420	2580	1640	2980	2030	3700
Zr	1280	2340	1500	2740	1740	3150	1850	3360
Ir	1300	2380	1500	2740	1740	3150	2450	4450
Mo	1380	2520	1630	2950	1900	3450	2610	4730
C	1530	2780	1680	3050	1880	3400	3700	6700
Ta	1780	3250	2050	3700	2300	4200	3000	5400
Re	1820	3300	2050	3700	2300	4200	3200	5800
W	1880	3400	2150	3900	2500	4500	3400	6200

Based on vapor pressure data of Reference 24.
Gaseous molecules taken as monatomic, except Se, Te, Sb, Bi taken as diatomic; C mean molecular weight taken as 24.

Table 3. Sublimation of some inorganic compounds in high vacuum

Compound	Temperature at which sublimation rate is						Melting point	
	10^{-5} cm/yr (1000 Å/yr)		10^{-3} cm/yr (0.0004 in/yr)		10^{-1} cm/yr (0.040 in./yr)			
	°C	°F	°C	°F	°C	°F	°C	°F
CsI	120	240	160	320	240	460	620	1150
MgO	540	1000	730	1350	1090	2000	2800	5100
MoS$_2$ [a]	730	1350	960	1760	1480	2700	-	-
ZrO$_2$	1070	1950	1320	2400	1480	2700	2700	4900
BeO	1340	2450	1480	2700	1700	3100	2550	4600
ThO$_2$	1400	2550	1600	2900	1900	3500	3300	6000

[a] For MoS$_2$, temperatures given are not for sublimation but for decomposition to S$_2$ (gas) and Mo (solid).

Table 4. Decomposition of polymers in high vacuum

Polymer	Temperature for 10% weight loss per year in vacuum		Quality of data	Literature references
	°C	°F		
Nylon	30 - 210	80 - 410	A	30, 45
Sulfide	40	100	C	48
Cellulose nitrate	40	100	C	48
Cellulose, oxidized	40	100	B	34
Methyl acrylate	40 - 150	100 - 300	A - C	31, 32, 48, 49
Ester	40 - 240	100 - 460	B - C	48, 50
Epoxy	40 - 240	100 - 460	B - C	48, 50
Urethane	70 - 150	150 - 300	C	48
Vinyl butyral	80	180	C	49
Vinyl chloride	90	190	A	35
Linseed Oil	90	200	C	48
Neoprene (chloroprene)	90	200	C	48
Alkyd	90 - 150	200 - 300	C - F	48, 51
Methyl methacrylate	100 - 200	220 - 390	A	31, 32, 49, 52, 53
Acrylonitrile	120	240	A	36, 52
Isobutylene-isoprene (butyl rubber)	120	250	D	55
Styrene-butadiene	130	270	C	48
Styrene	130 - 220	270 - 420	A	32, 33, 49, 55, 56, 57, 58
Phenolic	130 - 270	270 - 510	B - D	48, 50, 53, 59,
Butadiene-acrylonitrile (nitrile rubber)	150 - 230	300 - 450	B - D	54, 55
Vinyl alcohol	150	310	B	61
Vinyl acetate	160	320	—	62
Cellulose acetate butyrate	170	340	C	48
Cellulose	180	350	A	32, 34, 37
Carbonate	180	350	D	53
Methyl styrene	180 - 220	350 - 420	A	31, 32, 33, 56
Cellulose acetate	190	370	A	34
Propylene	190 - 240	370 - 470	A	32, 41, 64,
Rubber, natural	190	380	B	49
Isoprene	190	380	B	49, 63
Melamine	190	380	E	51
Silicone elastomer	200	400	D	55
Ethylene terephthalate (mylar, decron)	200	400	A	30
Isobutylene	200	400	B	32, 49, 63
Vinyl toluene	200	400	B	31, 32, 49
Styrene, cross-linked	230 - 250	440 - 490	A	39
Butadiene-styrene (GR-S - SBR)	240	460	B	49, 54, 63
Vinyl fluoride	240	460	B	40
Ethylene, low density	240 - 280	460 - 540	A	32, 33, 43, 50, 56, 63
Butadiene	250	490	B	49, 54, 63
Vinylidene fluoride-hexafluoropropene	250	490	A	65
Chlorotrifluoroethylene	250	490	A	32, 42, 65
Chlorotrifluoroethylene-vinylidene fluoride	260	500	A	65
Vinylidene fluoride	270	510	A	36, 40, 65
Benzyl	280	540	B	32, 41
Xylylene	280	540	B	32, 42
Ethylene, high density	290	560	A	32, 41, 43
Trivinyl benzene	290	560	A	36
Tetrafluoroethylene	380	710	A	40, 44, 47, 55, 66, 67
Methyl phenyl silicone resin	>380	>710	B	50

Table 5. Radiation dosages: ionization and displacement
produced by atomic particles in space

Radiation	Energy ev	Range gm/cm²	Ionization, erg/g-yr			Fraction of atoms displaced/yr		
			Extreme surface	Through 1 mg/cm²	Through 1 g/cm²	Extreme surface	Through 1 mg/cm²	Through 1 g/cm²
Inner radiation belt								
Protons	$10^3(?,-7 \times 10^2)$	$10^{-6}(?) \times 10^3$	$10^{12}(?)$	10^{11}	10^7	$10^{-1}(?)$	10^{-5}	10^{-9}
Electrons	$<2 \times 10^4, 1 \times 10^6$	$10^{-3}-10^0$	$10^{14}(?)$	10^{14}	0	$10^{-10}-10^{-8}$	$10^{-10}-10^{-8}$	0
Bremsstrahlung	$<2 \times 10^4, 1 \times 10^6$	$10^{-1}-10^1$	$10^7(?)$	10^7	10^7-10^8	$<10^{-13}$	$<10^{-13}$	$<10^{-13}$
Total			$10^{14}(?)$	10^{14}	10^7-10^8	$10^{-1}(?)$	10^{-5}	10^{-9}
Due principally to b			e	e	γ, p	p(?)	p	p
Outer radiation belt								
Electrons	$2 \times 10^4-5 \times 10^6$	$10^{-3}-10^0$	$10^{13}-10^{15}$	$10^{13}-10^{15}$	10^3	$10^{-12}-10^{-10}$	$10^{-12}-10^{-10}$	10^{-13}
Bremsstrahlung	$2 \times 10^4-5 \times 10^6$	$10^{-1}-10^1$	10^7-10^9	10^7-10^9	10^6-10^8	$<10^{-15}$	$<10^{-15}$	$<10^{-15}$
Total			$10^{13}-10^{15}$	$10^{13}-10^{15}$	10^6-10^8	$10^{-12}-10^{-10}$	$10^{-12}-10^{-10}$	10^{-13}
Due principally to			e	e	γ	e	e	e
Solar flare high energy particles								
Protons	$2 \times 10^7-10^9$	10^0-10^3	10^5-10^6	10^5-10^6	10^4-10^5	$10^{-12}-10^{-11}$	$10^{-12}-10^{-11}$	$10^{-13}-10^{-11}$
Electrons	$\sim 5 \times 10^4$	10^{-2}	$10^2-10^9(?)$	$10^7-10^9(?)$	0	0	0	0
Bremsstrahlung	$\sim 5 \times 10^4$	10^0-10^1	$10^2-10^4(?)$	$10^2-10^4(?)$	$10^4-10^5(?)$	0	0	0
Total			10^5-10^6	$10^5-10^9(?)$	10^4-10^5	$10^{-12}-10^{-11}$	$10^{-12}-10^{-11}$	$10^{-13}-10^{-11}$
Due principally to			e(?)	e(?)	p(?)	p	p	p
Solar flare low energy particles								
Protons	$5 \times 10^6-2 \times 10^7$	$10^{-6}(?)-10^{-5}(?)$	0	0	0	$<10^0$	0	0
Electrons	$2 \times 10^0-10^1$	10^{-3}	0	0	0	0	0	0
Bremsstrahlung	$2 \times 10^0-10^1$	$10^{-6}(?)-10^3$	0	0	0	0	0	0
Total			0	0	0	$<10^0$	0	0
Due to						p		
Steady solar emission								
Protons	$\sim 10^0-10^3$	$10^{-8}-10^{-6}(?)$	0	0	0	$0-10^0$	0	0
Electrons	10^0	10^{-8}	0	0	0	0	0	0
Bremsstrahlung	10^0	10^{-7}	0	0	0	0	0	0
Total			0	0	0	$<10^0$	0	0
Due to						p		
Cosmic rays								
Protons	10^8-10^{10}	$>10^{-1}$	10^2-10^3	10^2-10^3	10^2-10^3	$10^{-14}-10^{-13}$	$10^{-14}-10^{-13}$	$10^{-14}-10^{-12}$

a After Jaffe and Rittenhouse (1).

b e electron, p proton, γ bremsstrahlung photon

Table 6. Summary, radiation dosages in space produced by atomic particles

Radiation	Ionization, erg/g-yr		Fraction of atoms displaced/yr		
	Surface and through 1 mg/cm^2	Through 1 g/cm^2	Exposed surface	Through 1 mg/cm^2	Through 1 g/cm^2
Inner radiation belt	10^{14}(?)	10^7-10^8	10^{-1}(?)	10^{-5}	10^{-9}
Outer radiation belt	10^{13}-10^{15}	10^6-10^8	10^{-12}-10^{-10}	10^{-12}-10^{-10}	10^{-13}
Solar emission (flares except as noted)	10^7-10^9(?)	10^4-10^5	10^{-12}-10^0(a)	10^{-12}-10^{-11}	10^{-13}-10^{-11}
Cosmic rays	10^2-10^3	10^2-10^3	10^{-14}-10^{-13}	10^{-14}-10^{-13}	10^{-14}-10^{-13}

[a]May be displaced by steady solar emission

Table 7. Radiation dose producing appreciable change in
engineering properties of various materials

Material	Properties	Ionization erg/g	Fraction of atoms displaced
Plastics			
Tetrafluoroethylene	in air, mechanical, electrical	10^6-10^7	-
	no air, mechanical, electrical	10^7- 0^9	-
Other plastics	optical transmission	10^6-10^{11}	-
	dimensions, mechanical, electrical[a]	10^7-10^{11}	-
Elastomers	mechanical	10^8-10^{10}	-
Oils and greases	lubrication, consistency	10^9-10^{12}	-
Ceramics			
Glass	optical transmission	10^5-10^{10}	10^{-11}-10^{-7}
	dimensions, mechanical	$\geq 10^{11}$	$\sim 10^{-7}$
	electrical	$> 10^{11}$	10^{-7}-10^{-6}
Fused silica	optical transmission	10^7-10^{11}	10^{-9}-10^{-5}
Crystalline	optical transmission	10^5-10^{11}	10^{-8}-10^{-4}
	dimensional, mechanical	$> 10^{11}$	10^{-4}-10^{-2}
	electrical[b]	$> 10^{11}$	10^{-3}-10^{-1}
Semiconductor (devices)	minority carrier effects	-	10^{-12}-10^{-10}
	majority carrier effects	-	10^{-9}-10^{-6}
Metals	ferromagnetism	-	10^{-6}-10^{-5}
	mechanical	-	10^{-4}-10^{-3}
	electrical	-	10^{-3}-10^{-2}

[a]Temporary increase in electrical conductivity during irradiation at dose rates $\sim 10^6$ erg/g-yr.

[b]Temporary increase in electrical conductivity during irradiation at dose rates $\sim 10^8$ erg/g-yr.

Table 8. Damage to engineering properties by corpuscular radiation in space

Exposure time, months to years

Material	Properties	Inner radiation belt			Outer radiation belt		Solar flare and steady emission			Cosmic rays
		Exposed surface	Through 1 mg/cm²	Through 1 g/cm²	Surface and through 1 mg/cm²	Through 1 g/cm²	Exposed surface	Through 1 mg/cm²	Through 1 g/cm²	Surface and through 10 g/cm²
Plastics										
Tetrafluoroethylene	in air, mechanical electrical	-	all	all	all	all	-	all(?)	none	none
Other plastics	no air, mechanical, electrical	all	all	most	all	most	most(?)	most(?)	none[a]	none
	optical dimensions, mechanical, electrical	all	all	sens	all	sens	sens (?)	sens (?)	none[a]	none
Elastomers	mechanical	all	all	sens	all	sens	sens (?)	sens.(?)	none	none
Oils and greases	lubrication, consistency	all	all	none	all	none	none(?)	none	none	none
Ceramics										
Glass	optical transmission	all	all	most	all	sens	all(?)	most(?)	sens.	none
	dimensions, mechanical, electrical	all	all	none	all(?)	none	all(?)	none	none	none
Fused silica and crystalline ceramics	optical transmission	all	all	sens.	all	sens.	all(?)	sens. (?)	none	none
Crystalline	dimensions, mechanical electrical	all(?)	all(?)	none[b]	most(?)	none[b]	all(?)	none[a]	none	none
Semiconductor (devices)	minority carrier effects	all	all	all	most	none[b]	all(?)	sens.	sens.	none
	majority carrier effects	all	all	sens.	none	none	all(?)	none	none	none
Metals	ferromagnetism	all	all	none	none	none	all(?)	none	none	none
	mechanical, electrical	all(?)	none	none	none	none	all(?)	none	none	none

None: no damage of engineering significance in the usual applications
Sens: more sensitive materials and properties of this class affected

Most: most materials and properties of this class affected
All: major changes in engineering properties significant in usual applications

[a] temporary increase in electrical conductivity may occur during flare emissions
[b] temporary increase in electrical conductivity may occur in sensitive materials

Table 9. Cumulative energy distribution in sunlight,
at Earth's distance from the Sun[a]

Up to wavelength, Å	Fraction of total energy	Energy, at sunspot maximum (including flares) erg/cm^2-yr
0.1	10^{-11}	$10^2 - 10^{3}$[b]
1	10^{-11}	$10^2 - 10^3$
10	10^{-8}	$10^5 - 10^6$
100	10^{-6}	$10^7 - 10^8$
500	10^{-6}	10^8
1,000	10^{-5}	10^8
1,500	10^{-5}	10^9
2,000	10^{-4}	4×10^9
2,500	1.3×10^{-3}	6×10^{10}
3,000	1.2×10^{-2}	5×10^{11}
4,000	9×10^{-2}	4.0×10^{12}
5,000	0.24	1.1×10^{13}
6,000	0.37	1.6×10^{13}
7,000	0.49	2.2×10^{13}
8,000	0.58	2.6×10^{13}
9,000	0.65	2.9×10^{13}
10,000	0.71	3.2×10^{13}
15,000	0.88	3.9×10^{13}
20,000	0.94	4.2×10^{13}
30,000	0.98	4.3×10^{13}
70,000	0.999	4.4×10^{13}

[a]Data above 2000 Å from Johnson (216).

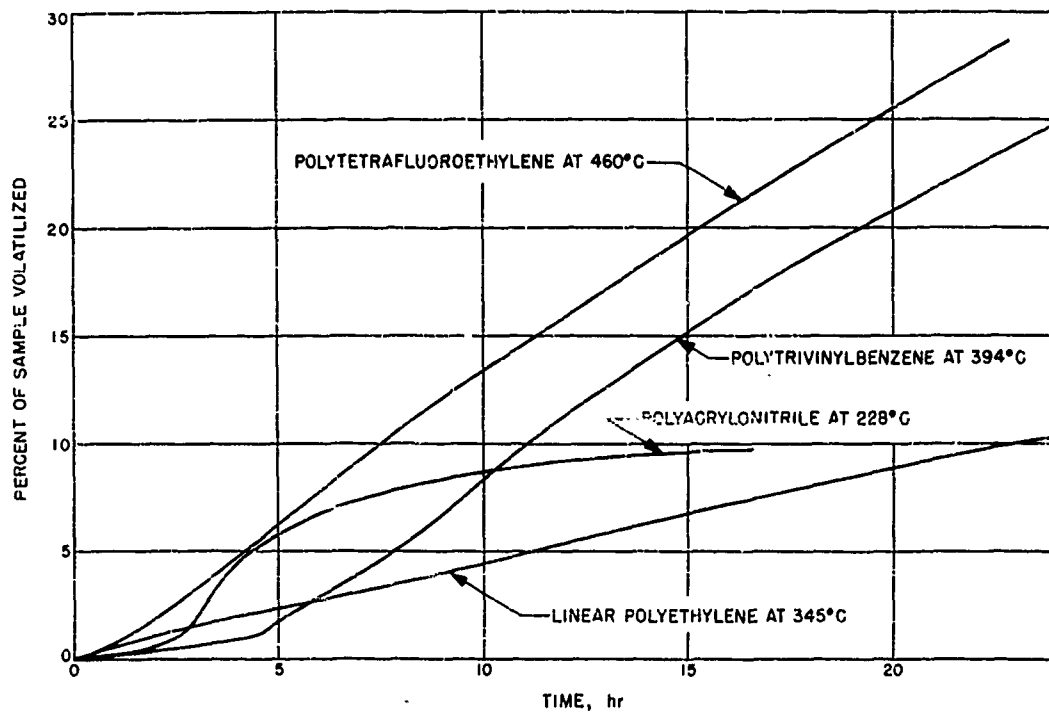[b]10^9 to 10^{10} photons/cm^2-yr shorter than 0.1 Å.

Fig. 1. Typical curves for weight loss of polymers in vacuum as a
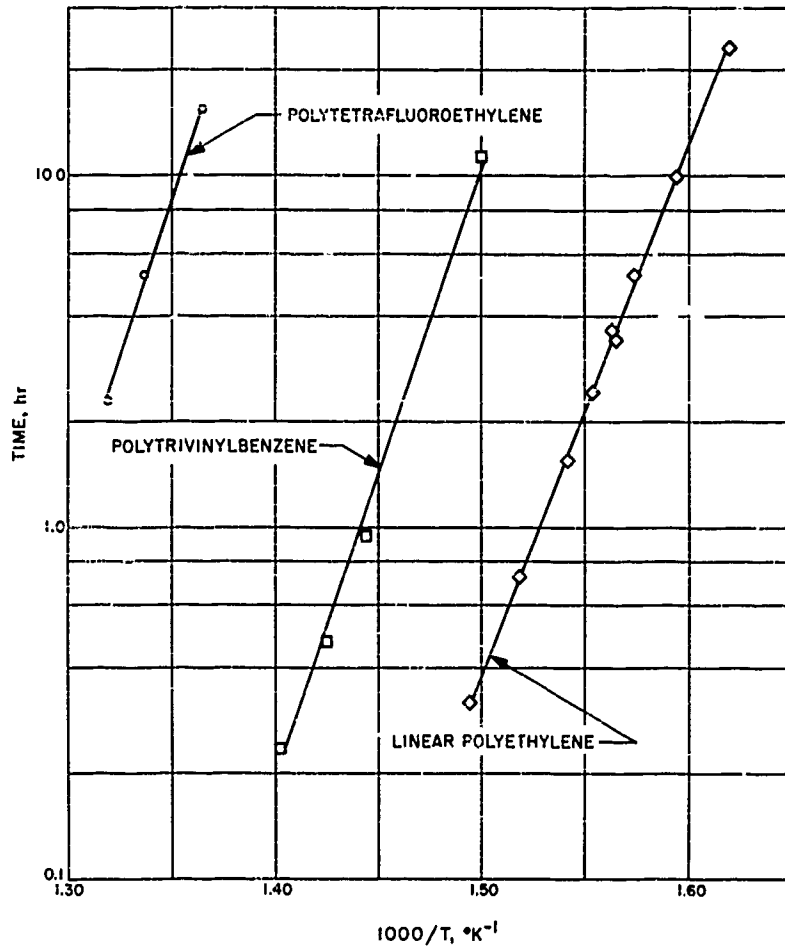function of time. After Madorsky and Straus (32, 36, 47).

Fig. 2. Time-temperature relation for 10% weight loss of
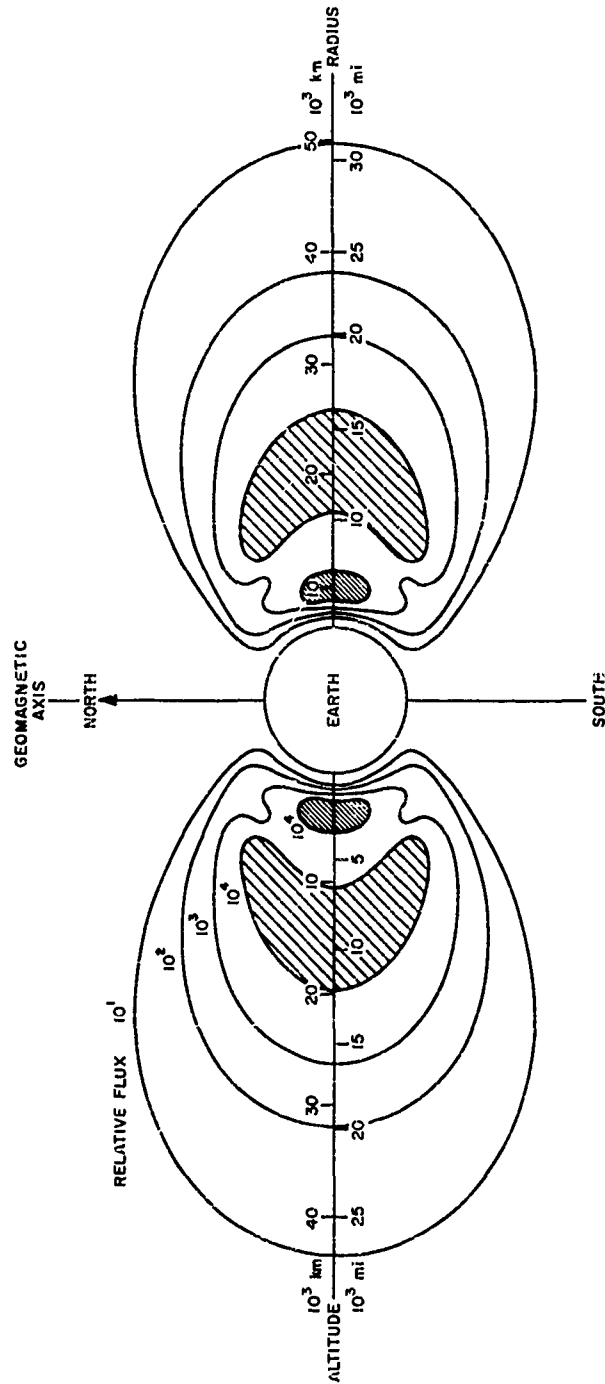polymer in vacuum. Data of Madorsky and Straus
(32, 36, 41, 47).

Fig. 3. The Earth's radiation belts. Cross-section taken through the Earth's magnetic poles.
Contours of constant electron counting rate on relative scale; these contours vary with time and
with the characteristics of the electron detector used. After Van Allen (99), with modifications
based on data of Arnoldy, Hoffman, and Winckler (100), Fan, Meyer, and Simpson (101),
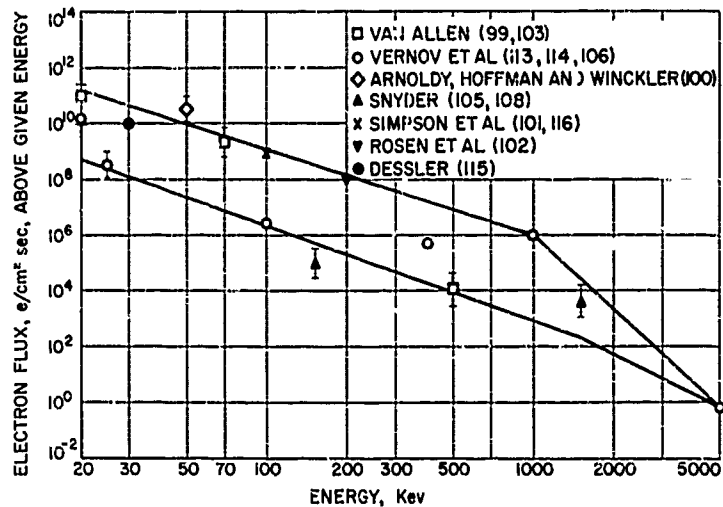Rosen, Farley, and Sonett (102).

Fig. 4. Electron flux at peak of outer radiation belt.
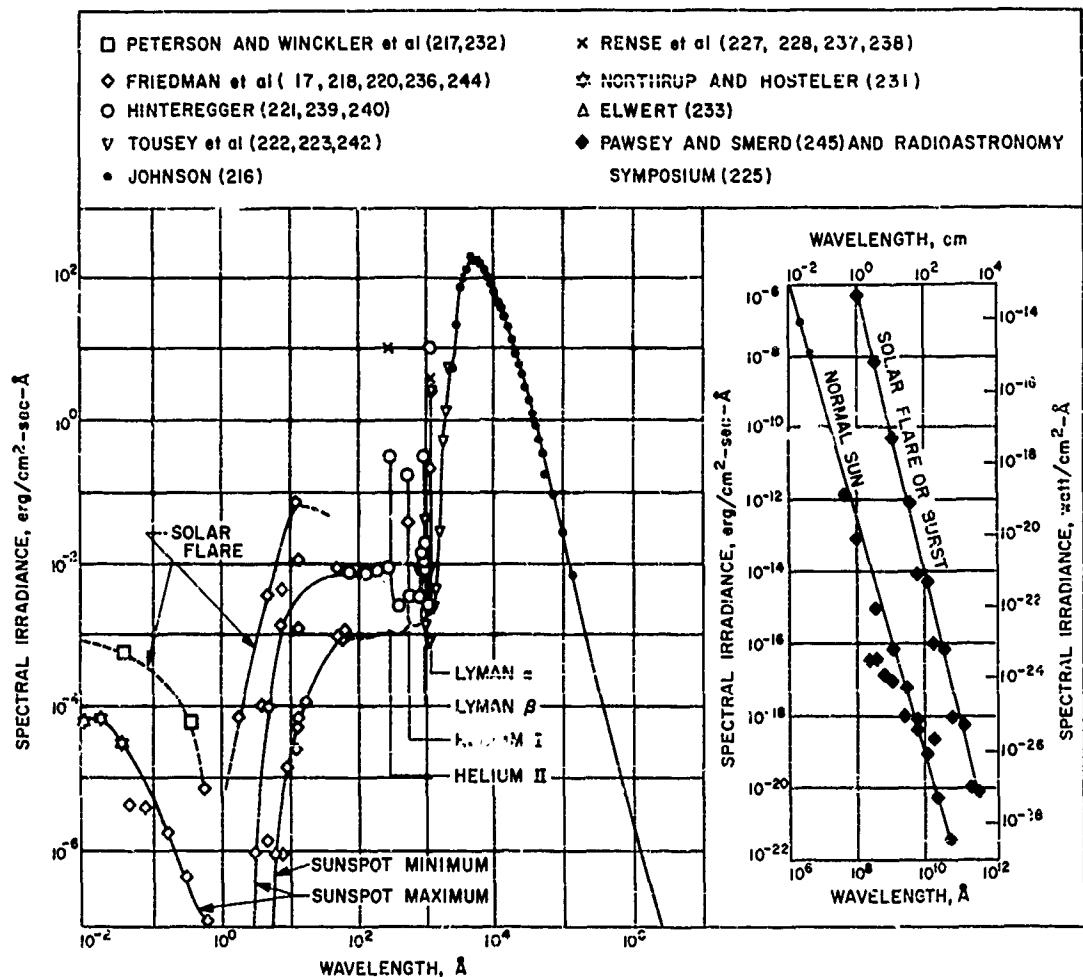Averaged over all directions.

Fig. 5. Solar electromagnetic radiation, at Earth's distance from the Sun. Insert shows, on a smaller scale, the extension of the spectrum to radio wavelengths. Below 1000 Å and above 1 cm, irradiance varies over the sunspot cycle, and higher intensities occur for intervals of seconds to hours during solar bursts and flares. Very large flares may give somewhat more intensity than shown. The curves are smoothed over most spectral lines. Data from literature (17, 18, 106, 216 - 249).
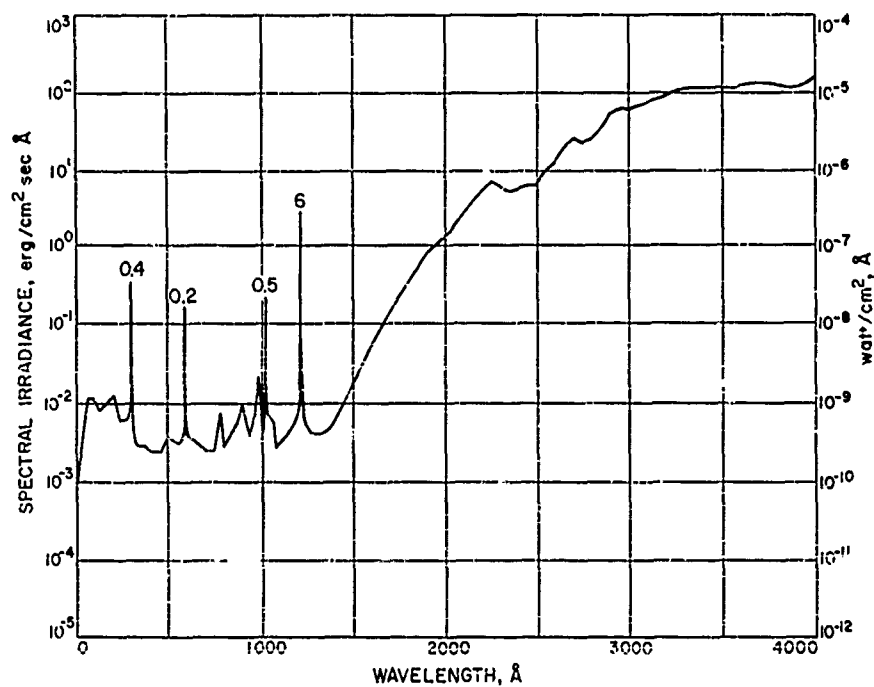
Fig. 6. Solar ultraviolet spectrum, at Earth's distance from the Sun and sunspot maximum. Numbers on prominent emission lines show intensity, in erg/cm^2-sec, integrated over the line. Curve is smoothed over most spectral lines. Flare radiation not shown.
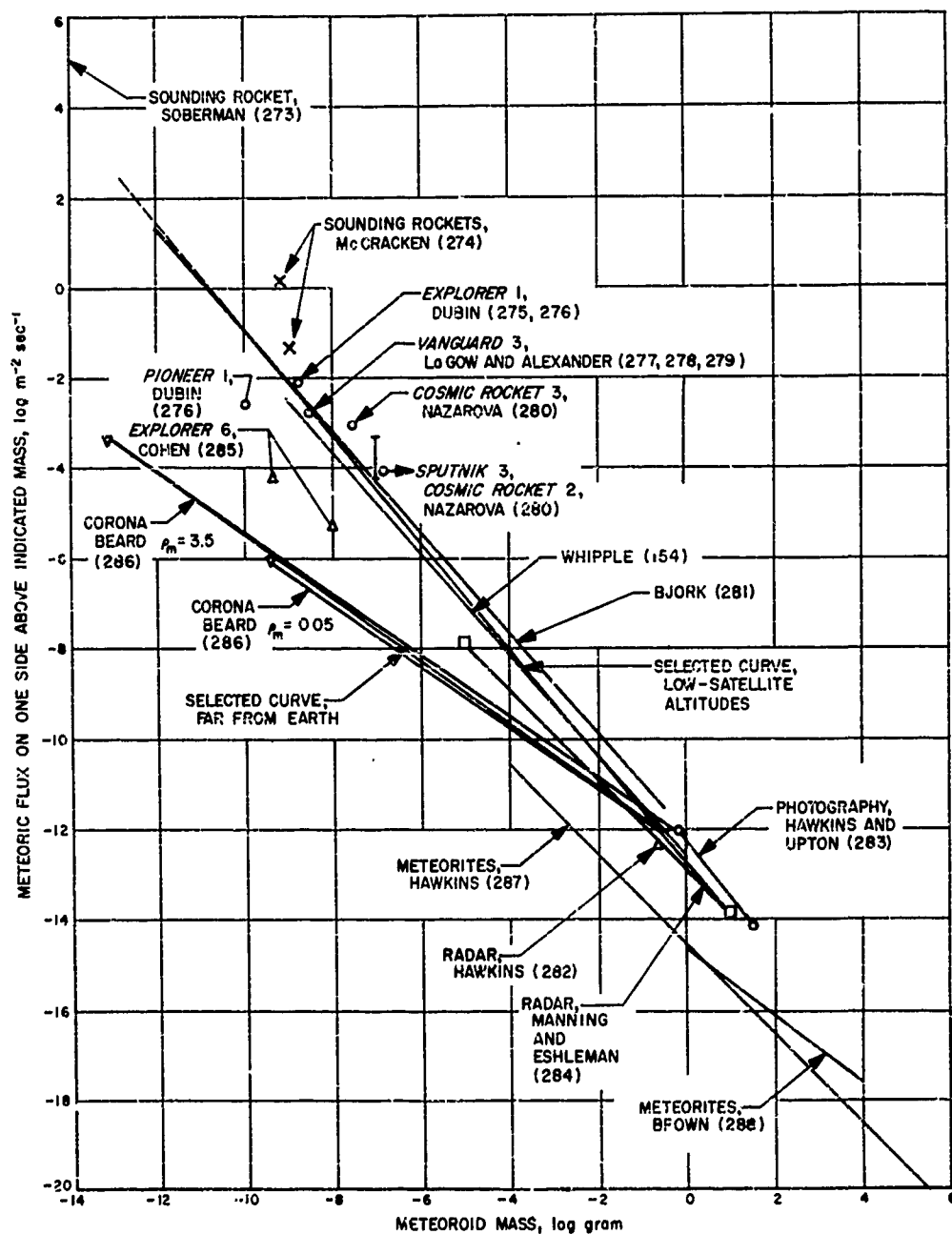
Fig. 7.   Meteoric flux in vicinity of Earth's orbit.   Below 10^{-6} g, velocity of 15 km/sec and momentum calibration of meteoroid gages are assumed (154).
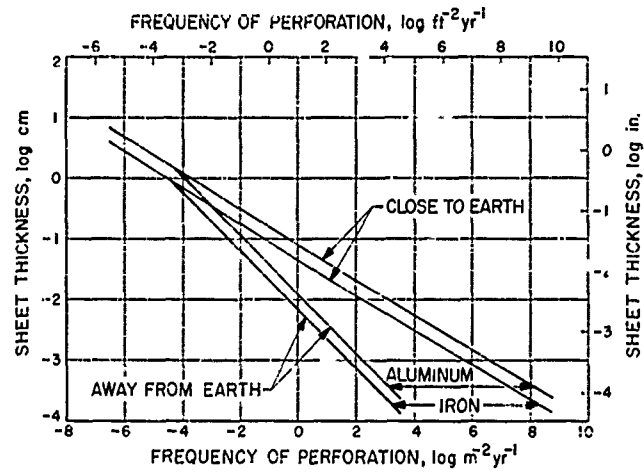
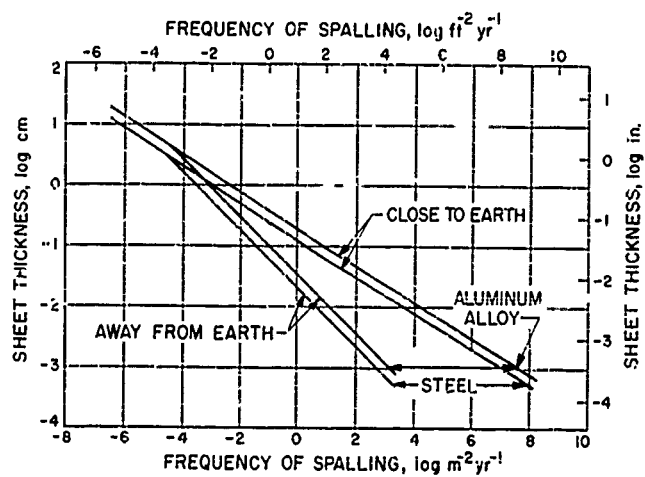Fig. 8. Frequency of meteoric perforation in vicinity of Earth's orbit.

Fig. 9. Frequency of back-surface spalling
produced by meteoric impact in
vicinity of Earth's orbit.

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